U.S. Department of Commerce
National Oceanic and Atmospheric
Administration

U.S. Nuclear Regulatory
Commission
NUREG/CR-1486

Hydrometeorological Report No. 53

# SEASONAL VARIATION OF 10-SQUARE-MILE PROBABLE MAXIMUM PRECIPITATION ESTIMATES, UNITED STATES EAST OF THE 105TH MERIDIAN

Prepared by
Francis P. Ho and John T. Riedel
Hydrometeorological Branch
Office of Hydrology
National Weather Service
Washington, D.C.
April 1980

## TABLE OF CONTENTS

## FIGURES

TABLES

# SEASONAL VARIATION OF 10-SQUARE-MILE PROBABLE MAXIMUM PRECIPITATION ESTIMATES UNITED STATES EAST OF THE 105th MERIDIAN

Francis P. Ho and John T. Riedel
Hydrometeorological Branch
Water Management Information Division
Office of Hydrology
National Weather Service, NOAA
Silver Spring, Maryland

ABSTRACT.  Estimates of the upper limit to rainfall that the atmosphere can produce (probable maximum precipitation) are given in this study for durations from 6 to 72 hours for each month of the year for 10 mi$^2$ areas.  The results are in a generalized form, that is, on maps allowing use for planning and design of any present or proposed hydrologic structure for the United States east of the 105th meridian.  The probable maximum precipitation estimates show a smooth variation with duration, season, and location.

## 1.  INTRODUCTION

### 1.1  Authorization

This study was authorized and funded through Interagency Agreement No. NRC-01-77-113 between the Nuclear Regulatory Commission (NRC) and the National Oceanic and Atmospheric Administration (NOAA) dated June 2, 1977. The Agreement was extended to October 1, 1979, by an amendment dated May 20, 1979.

### 1.2  Purpose

The purpose of the study is to give seasonal variation of probable maximum precipitation (PMP) estimates for 10 mi$^2$ areas for the United States east of the 105th meridian.  PMP estimates for durations of 6 to 72 hours, by 6-hr increments are required.

### 1.3  Scope

PMP estimates for 6, 24, and 72 hours are given on generalized maps for each midmonth for 10 mi$^2$ areas.  While smaller sized areas have greater PMP values, especially for the warm season, they will not be defined in this study.  For the winter season, PMP for smaller areas are not appreciably different from the 10-mi$^2$ values in this study.

All-season estimates of PMP, Hydrometeorological Report (HMR) No. 51, *Probable Maximum Precipitation Estimates, United States East of the 105th Meridian*, (Schreiner and Riedel 1978) set the greatest values that can be

reached at some time during the year. They are accepted as upper bounds for the present study.

## 1.4 Definitions

*Probable maximum precipitation* (PMP) means *the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a certain time of year.* (American Meteorological Society 1959). Realizing there are yet unknowns in the physical processes responsible for extreme rainfall, we refer to PMP values as estimates.

*Generalized* PMP estimates are estimates determined for large regions that are now required or one would expect will be needed in the future. These are frequently presented as a series of isolines on a map for a given area size and duration.

*All-season* PMP is the greatest PMP regardless of season. For the region of this study one can generally say that for all durations, the all-season PMP will fall sometime between June and September for every point. Our problem is to determine the variation from this all-season estimate for each month of the year.

## 1.5 Previous Study

The only other study covering seasonal variation of PMP for the entire region is HMR No. 33 (Riedel et al. 1956). Because the all-season values of HMR No. 51 differ from those of HMR No. 33, it follows that the estimates for each month in HMR No. 33 also need revision. All facets of PMP for the region were restudied and therefore the seasonal values differ from those in HMR No. 33.

## 2. BASIC DATA

## 2.1 Background

As in all PMP studies, basic data are the extreme record storm rainfalls. *Storm Rainfall in the United States, Depth-Area-Duration Data* (Corps of Engineers 1945- ) is a kept-up-to-date catalog of many of the most extreme areal rainfalls. The data are maximum areal depths for standard area sizes and durations. Data for more than 600 storms have been published in this catalog. Additional data come from unofficial sources developed by the Hydrometeorological Branch (Shipe and Riedel 1976).

Most of the storms include data from surveys after the storm or resulting flood, sometimes called *bucket surveys*, in which additional rainfall measurements are found. Some of these values are measured in regular rain gages, privately owned or owned by local agencies or companies but not included in usual published records. Other values are measured in small *test tube* type gages, oil cans, or buckets. Such unofficial catches are accepted after checks against other observations and weather patterns, discussions with

observers, and more recently, against radar echoes and satellite pictures. It turns out that the most extreme point rainfalls of record are almost entirely from unofficial sources. This should be expected since there is practically no chance that the most extreme rainfall of a storm would occur over a preselected gage site. A shortcoming is that only very limited surveys and studies have been made for "out of season" (that is out of the season giving most intense rainfalls of the year) storms. Thus, we must augment our sample with extremes from regularly reporting precipitation stations and recognize that these values may not include the most extreme falls.

## 2.2 Available Station Rainfall Data

Table 1 lists several data sets that were surveyed for obtaining the greatest rainfalls for each month.

### 2.2.1 Storm Rainfall

This means *Storm Rainfall in the United States, Depth-Area-Duration Data* (Corps of Engineers 1945- ) and the augmented computer file of storm data (Shipe and Riedel 1976). The greatest value for 6, 12, 24, 48, and 72 hours for each month were used from these sources.

### 2.2.2 Maximum 1-Day or 24-Hr Values, Each Month

These values (Jennings 1952) are for regularly reporting stations for the period of record through 1949. Because nonrecording stations are more numerous than recording stations and have longer records, the maximum values generally are from nonrecording stations.

### 2.2.3 Maximum 6-, 12- and 24-Hr Values, Each Month

For 28 of the 37 states involved in this study, there are published (U.S. Weather Bureau 1951-61) maximum observed depths at recording stations for these durations for the period beginning, in most cases, in the 1940's and ending in 1950. Exceptions are the few recorders going back many years at "first-order" Weather Bureau (now National Weather Service) stations.

### 2.2.4 Maximum Recorded Rainfall at First-Order Stations

A paper (Jennings 1963) published the greatest depths at first-order stations for durations from 5 minutes to 24 hours for about 200 stations in the study region. This is for the period of record through 1961.

### 2.2.5 Data Tapes, Selected Stations

For about 50 stations in our study region, daily rainfall records have been put on magnetic tapes for the period 1912-61. From these tapes we can extract 1-, 2-, and 3-day maxima for each of the 12 months.

4

*Table 1.--Data sources for determining maximum station precipitation of record*

| Item | Type of Data | Period of record | Remarks |
|------|-------------|------------------|---------|
| *United States Data* | | | |
| Storm Rainfall | Primarily maximum known areal depths | For greatest known storms - kept up to to date. | Mainly for warm season |
| Technical Paper No. 16 | Maximum 1-day or 24-hr values, each month for regular reporting stations | Through 1949 | |
| Technical Paper No. 15 | Maximum 1-, 2-, 3-, 6-, 12-& 24-hr values for each month | Through 1950 | Available for 28 of the 37 states in study region |
| Technical Paper No. 2 | Maximum recorded rainfall 5 min to 24 hr for 296 1st order stations | Through 1961 | |
| Data tapes | Daily precipitation | 1912-1961 | Available for stations in study region |
| Data tapes | a. daily & b. hourly precipitation for regular reporting stations | 1948-73 | More than 6500 stations |
| *Canadian Data* | | | |
| Storm Rainfall | Similar to U.S. storm rainfall | | |
| Station Maxima | Daily Observation | 1941-1970 | See section 2.2.7 |

## 2.2.6   Data Tapes, 1948-73

These tapes include all observed hourly and daily rainfalls for the period measured both at recording and nonrecording stations, updating to 1973 the published data of pars. 2.2.2 to 2.2.5 for the durations we are interested in.

## 2.2.7   Canadian Data

The Canadians have summarized maximum rainfall depths in much the same way we have in the United States. They maintain a catalog *Storm Rainfall in Canada* of greatest areal rainfall depths (Atmospheric Environment Service 1961- ). Another publication (Atmospheric Environment Canada 1973) gives the greatest single observed value for one day at each observing station for the period 1941-70. Yet another source (Department of Transport) lists the greatest single observed value for a day in the period 1931-58. A list of station locations (Department of Transport, Meteorological Branch 1970) was helpful in locating extremes near the northern bound of our study region.

## 3.   APPROACH TO PMP

### 3.1   Summary

Central to this study, as already mentioned, is HMR No. 51. For at least one midmonth the values of the present study reach the all-season PMP of HMR No. 51 for every geographical point. The basic approach used in HMR No. 51 is the approach adopted here. We will not repeat the various techniques, steps, and tests fully detailed in that report. More generally, a manual of PMP (World Meteorological Organization 1973) which summarizes PMP procedures that have been used in the United States is recommended for any reader who wishes to pursue the topic further.

Development of PMP for each month consisted of the following operations on selected major record storm rainfalls.

a.   Moisture maximization

b.   Transposition

c.   Envelopment

Brief discussions of these items follow. At times we extract liberally from HMR No. 51.

### 3.2   Selected Major Storm Values

From the data sources listed we extracted those values that could significantly influence the level of PMP after they are moisture maximized (par. 3.3) and transposed (par. 3.4), for September through June and any portion of the study region. This was done by first plotting the most extreme depths for a given duration from *Storm Rainfall in the United States* on 12 maps, one for each month. We then extracted the greatest station values from the other data sources and added them to the plotted maps if they were of the same general level or greater than those already on the maps. Such maps were plotted for extreme values for durations of 6, 12, 24, 48 and 72 hours. On these

maps we also plotted the most extreme rainfall values for the region adjoin-
ing the United States from the Canadian data sources.

Table 2 lists the storms selected chronologically by month. We show the
storm location by latitude, longitude, town, and State. The storm number we
used is given, as well as the Corps of Engineers' assignment number (if
there is one) from *Storm Rainfall in the United States* (Corps of Engineers
1945- ) and the source of the data. The observed depth for the most criti-
cal duration is given. Other information in table 2 is explained in par.
3.5.

Figures 1a, 1b, and 1c show the locations of these most important storms
together with the observed rainfall depths for 6-, 24-, and 72-hr durations
respectively. The month of occurrence is also given.

Table 3 lists the more important storms selected from the Canadian data.
These have a bearing on the magnitude of PMP near the U.S. border.

## 3.3  Moisture Maximization

### 3.3.1  The Concept

Moisture maximization is increasing storm rainfall depths for the storm
location and season, for higher atmospheric moisture than was available in
the actual storm.

Signficant precipitation results from lifting moist air. Processes caus-
ing this lifting, associated with horizontal convergence, have been de-
scribed in numerous texts. Various attempts at developing a model that will
reproduce extreme rainfalls are hampered by the lack of sufficient data
within storms to adequately check the magnitudes of horizontal convergence,
vertical motion, and other parameters. Since measurements of these para-
meters during severe storms are not readily obtainable, the solution has
been to use extreme record storm rainfalls as an indirect measure of para-
meters, other than moisture, that are important to such events.

We thus adjust storm rainfalls of record to the equivalent that would have
occurred with maximum moisture and make the following assumption: The
sample of extreme storms is sufficiently large so that near optimum "mechan-
ism" (or efficiency) has occurred. By "mechanism" is meant a combined
measure of all the important parameters to rainfall production, except
moisture. The assumption thus circumvents a quantitative evaluation of
"mechanism" and results in increasing the observed storm rainfall, assumed
to occur with near optimum "mechanism", by an adjustment for moisture.

This assumption is probably most realistic when considering all-season PMP.
Having to spread the storm sample throughout the 12 months weakens the
assumption and we compensate by more liberal envelopment (par. 3.6).

### 3.3.2  Atmospheric Moisture

The best measure of atmospheric moisture through depth can be obtained
from radiosonde observations. Specifically for the present study we have

*Table 2.--Major storms selected for moisture maximization and transposition*

| Date | Storm Number | City | State | Lat. | Long. | CoE[1] Assignment Number | Source* | Gridpoint(s) transposed to V̄ | Critical Duration(s) (hrs) | Obs. Depth (in.) | Controlling for grid point(s) | Total storm adjustment (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/18-21,1935 | 2 | Hernando | MS | 34°50 | 90°00 | LMV1-19 | STR | 6,7,10,11,13 | 72 | 13.4 | 6 | 70 |
| 1/1-2,1941 | 3 | Pigeon River | MI | 48°00 | 89°42 | T.P.16 | | 9,10 | 24 | 4.7 | 9,10 | 150 |
| 1/4,1949 | 4 | Coleraine | MN | 93°28 | 47°16 | | DTD | 1,5,9 | | | | |
| 1/22-27,1949 | 5 | Timbo | AR | 35°52 | 92°19 | SW3-10 | STR | 6,7,8,10 | 6 | 7.5 | 6,13 | 70 |
| | | | | | | | | 11,12,13 | 24 | 11.7 | 10 | 74 |
| 1/31-2/2,1920 | 6 | St.Augustine | FL | 29°51 | 81°21 | | STR | 12,15 | | | | |
| 2/14-19,1938 | 8 | Calvin | OK | 34°56 | 96°15 | SW2-17 | STR | 6,7,10,11 | 6 | 4.8 | 6 | 78 |
| 2/6,1955 | 9 | Oberlin | LA | 30°36 | 92°47 | | DTD | 12,15,17 | | | | |
| 2/22,1961 | 10 | Bessemer | AL | 33°22 | 87°01 | | DTD | 12,15,17 | 72 | 13.5 | 17 | 150 |
| 2/10,1966 | 11 | Leesville | LA | 31°09 | 93°16 | | T.P.16 | 7,8,11,12,15 | | | | |
| 2/26,1969 | 12 | Mt.Washington | NH | 44°16 | 71°18 | | DTD | a | 72 | 14.1 | | |
| 2/10-11,1970 | 13 | Mt.Washington | NH | 44°16 | 71°18 | | DTH | a | 24 | 10.2 | | |
| 2/1,1973 | 14 | Spearsville | LA | 32°56 | 92°36 | | DTH | 7,8,11,12 | 6 | 10.6 | 8,12 | 141 |
| | | | | | | | | | | | 7,11 | 116 |
| 2/23-25,1875 | 15 | Clingman Dome | NC | 35°33 | 83°30 | | STR | 14,16 | 6 | 5.8 | 16 | 90 |
| 3/26-4/1,1886 | 16 | Pinkbeds | NC | 35°22 | 82°47 | | STR | 14 | | | | |
| 3/23-27,1913 | 17 | Bellefontaine | OH | 40°22 | 83°46 | OR1-15 | STR | 6,7,10,11,13 | 24 | 7.3 | 13 | 116 |
| | | | | | | | | | 72 | 10.4 | | |
| 3/24-28,1914 | 18 | Merryville | LA | 30°46 | 93°32 | LMV3-19 | STR | 8,12,15 | | | | |
| 3/11-16,1929 | 19 | Elba | AL | 31°25 | 86°04 | LMV2-20 | STR | 8,12,15 | 6 | 14.0 | 8,12,15 | 134 |
| | | | | | | | | | 24 | 20.0 | | |
| | | | | | | | | | 72 | 29.6 | | |
| 3/28-4/2,1945 | 20 | Van (nr) | TX | 32°20 | 95°42 | SW3-5 | STR | 8,12 | | | | |
| 3/25,1964 | 21 | Spruce Mt. | NC | 35°37 | 83°12 | | DTH | 14 | | | | |
| 3/16-17,1965 | 22 | Bayfield | WI | 46°53 | 90°49 | | DTD | 9,10,13 | | | | |
| | | | | | | | | | | | 1 | 110 |
| 3/2-5,1966 | 23 | Courtenay | ND | 47°14 | 98°35 | | STR | 1,5,9 | 24 | 4.7 | 5 | 116 |
| 3/14,1973 | 24 | Lead | SD | 44°21 | 103°46 | | DTD | 1,2,5,6,9,10 | 24 | 5.7 | 1,5,9 | 105 |
| | | | | | | | | | | | 2 | 135 |
| 4/22-24,1932 | 25 | Ellendale | ND | 46°29 | 99°45 | | STR | 1,5,6,9,10 | 6 | 3.0 | 5,9 | 149 |
| | | | | | | | | | | | 1 | 135 |

See last page for notes.

*Table 2.--Major storms selected for moisture maximization and transposition (continued)*

| Date | Storm Number | City | State | Lat. | Long. | CoE[1] Assignment Number | Source* | Gridpoint(s) transposed to ∇ | Critical Duration(s) (hrs) | Obs. Depth (in.) | Controlling for grid point(s) | Total storm adjustment (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4/11-14,1933 | 26 | Durham | NH | 43°08 | 70°56 | NA1-23 | STR | 17,18,20 | 6 | 4.9 | 18 | 150 |
| | | | | | | | | | | | 20 | 142 |
| 4/3-4,1934 | 27 | Cheyenne | OK | 35°37 | 99°40 | SW2-11 | STR | 7,8 | 6 | 17.3 | 7 | 148 |
| | | | | | | | | | 24 | 21.3 | 8 | 150 |
| 4/24-28, 1937 | 28 | Clear Spring | MD | 39°40 | 77°54 | SA5-13 | STR | 16,17,18 | | | | |
| 4/26, 1954 | 29 | Morris | MN | 45°35 | 95°55 | | T.P.16 | 5,6,9,10,13 | 24 | 6.9 | 9 | 148 |
| 4/23-24,1960 | 30 | Gurney | WI | 46°28 | 90°30 | | P.P.16 | 5,6,9,10,13 | | | | |
| 4/28, 1970 | 31 | Hazelton | ND | 46°29 | 100°17 | | DTH | 1,2,5,6,9,10 | 6 | 3.8 | 9 | 110 |
| 4/20-22, 1973 | 32 | Moberly | MO | 39°28 | 92°25 | | DTH | 9,10,11,13 | 24 | 8.3 | 13 | 122 |
| 4/12-14, 1974 | 33 | Magee | MS | 31°55 | 89°42 | | STR | 8,12,15 | | | | |
| 5/30-31, 1935 | 34 | Hale | CO | 39°36 | 102°08 | MR3-28a | STR | 3 | 6 | 16.5 | 3 | 128 |
| | | | | | | | | | 24 | 22.2 | | |
| 5/6-12,1943 | 35 | Warner | OK | 35°29 | 95°18 | SW2-20 | STR | 7,10,11 | 6 | 9.9 | 10 | 116 |
| | | | | | | | | | 24 | 17.2 | 11 | 134 |
| | | | | | | | | | 72 | 24.9 | 10,11 | |
| 5/30, 1949 | 36 | Thief Rvr Flls | MN | 48°07 | 96°11 | | DTD | 1,5,9 | | | | |
| 5/28, 1961 | 37 | Bar Harbor | ME | 44°23 | 68°12 | | DTD | 18,20 | | | | |
| 6/13-18, 1886 | 38** | Alexandria | LA | 31°19 | 92°33 | LMV4-27 | STR | 8,12 | | | | |
| 6/17-21, 1921 | 39 | Springbrook | MT | 47°18 | 105°35 | MR4-21 | STR | 1,2 | | | | |
| 6/14-15, 1942 | 40 | Warren 1SE | NH | 43°55 | 71°53 | | T.P.15 | 16,17,18,20 | | | | |
| 6/10-13, 1944 | 41 | Stanton | NE | 41°52 | 97°03 | MR6-15 | STR | 5,6,7,9,10 | 6 | 13.4 | 5,9 | 128 |
| | | | | | | | | 11,13 | | | 6,10 | 141 |
| | | | | | | | | | | | 11 | 148 |
| | | | | | | | | | | | 13 | 122 |
| 6/23-24, 1948 | 42 | Del Rio | TX | 29°22 | 100°37 | | STR | 4,8 | 24 | 26.2 | 4 | 121 |
| 6/23-28, 1954 | 43** | Vic Pierce | TX | 30°12 | 101°35 | SW3-22 | STR | 4,8 | 6 | 16.0 | 4 | 116 |
| | | | | | | | | | 24 | 26.7 | 8 | 150 |
| | | | | | | | | | 72 | 34.6 | 4,8 | |
| 6/30, 1962 | 44 | Cedar Is | NC | 34°57 | 76°17 | | DTD | 17 | | | | |
| 6/23-24, 1963 | 45 | David City | NE | 41°14 | 97°05 | | STR | 5,6,7,9,10,11 | 6 | 14.6 | 5 | 128 |
| | | | | | | | | | | | 6,9 | 134 |
| | | | | | | | | | | | 10,11 | 141 |

See last page for notes.

| Date | Storm Number | Location City | State | Lat. | Long. | CoE[1] Assignment Number | Source | Gridpoint(s) transposed to ∇ | Critical Duration(s) (hrs | Obs. Depth (in.) | Controlling for grid point(s) | Total storm adjustment (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/24, 1966 | 46 | Mellen Dam | ND | 47°21 | 101°19 | | STR | 1,2,5,6,9 | 6 | 11.1 | 1 | 148 |
| 6/9,1972 | 47 | Rapid City | SD | 44°12 | 103°31 | MR10-12 | STR | 2 | | | | |
| 6/20-22, 1972 | 48 | Bolivar | NY | 42°05 | 78°10 | | STR | 16,17,18,20 | 24 | 14.3 | 20 | 121 |
| | | | | | | | | | 72 | 18.5 | | |
| 9/8-10, 1921 | 49** | Thrall | TX | 30°35 | 97°18 | GM4-12 | STR | 4,8,12,15 | 24 | 36.5 | 8,12 | 114 |
| 9/17-19,1926 | 50 | Boyden | IA | 43°12 | 96°00 | MR4-24 | STR | 5,6,7,9,10,11 | 6 | 15.1 | 5,9 | 122 |
| | | | | | | | | 13 | 24 | 21.7 | 6,10 | 134 |
| | | | | | | | | | | | 7,11 | 141 |
| | | | | | | | | | | | 13 | 128 |
| 6/16-17,1932 | 51 | Westerly | RI | 41°22 | 71°50 | NA1-20 | STR | 16,17,18,20 | | | | |
| 9/1, 1940 | 52** | Ewan | NJ | 39°42 | 75°12 | NA2-4 | STR | 17,18 | 6 | 20.1 | 17 | 128 |
| | | | | | | | | | | | 18 | 122 |
| 9/2-6,1940 | 53 | Hallet | OK | 36°15 | 96°36 | SW2-18 | STR | 7,8,11,12 | 6 | 18.4 | 7,8,11,12 | 141 |
| | | | | | | | | | 24 | 23.6 | | |
| 9/3-7,1950 | 54** | Yankeetown | FL | 29°03 | 82°42 | SA5-8 | STR | 8,12,15,17 | 24 | 38.7 | 8 | 100 |
| | | | | | | | | | | | 12,15 | 98 |
| 10/27-30,1900 | 55 | Bedford | IA | 40°53 | 94°34 | UMV1-7A | | 6,9,10 | 6 | 5.0 | 9 | 122 |
| 10/7-11,1903 | 56 | Petersburg | NJ | 40°55 | 74°10 | GL4-9 | STR | 16,17,18 | | | | |
| 10/17-22,1941 | 57** | Trenton | FL | 29°48 | 82°57 | SA5-6 | STR | 8,12,15,17 | 24 | 30.0 | 8,12,15 | 116 |
| | | | | | | | | | 72 | 35.0 | 17 | 110 |
| 10/11-18,1942 | 58 | Big Meadows | VA | 38°31 | 78°26 | SA1-28A | STR | 16,17,18 | 24 | 13.4 | 18 | 150 |
| | | | | | | | | | 72 | 18.7 | | |
| 10/9-10,1954 | 59 | Aurora | IL | 41°45 | 88°20 | | STR | 10,13 | 24 | 11.7 | 10 | 150 |
| 10/25,1959 | 60 | Pinkham Notch | NH | 44°16 | 71°15 | | DTD | 16,18,20 | | | | |
| 10/3-4,1969 | 61 | Hartford | CT | 41°50 | 72°54 | | STR | 15,16,17,18 | | | | |
| 10/4, 1971 | 62 | Mt. Weather | VA | 39°04 | 77°53 | | DTH | 16,17,18 | | | | |
| 10/10-11,1973 | 63 | Enid | OK | 36°25 | 97°52 | | STR | 6,7,10,11 | 6 | 16.9 | 11 | 116 |
| | | | | | | | | | 24 | 18.6 | 6,10 | 100 |
| | | | | | | | | | | | 7 | 110 |
| 11/1, 1909 | 64 | Ironwood | MI | 46°27 | 90°11 | | T.P.16 | 5,6,9,10 | | | | |
| 11/7, 1915 | 65 | Crosby | ND | 48°54 | 103°18 | | T.P.16 | 1,2,5,6 | | | | |
| 11/12-15,1922 | 66 | Lakeside | LA | 30°02 | 92°30 | LMV3-29 | STR | 8,12,15 | | | | |

See last page for notes.

Table 2.—*Major storms selected for moisture maximization and transposition (continued)*

| Date | Number | Location City | State | Lat. | Long. | CoE[1] Assignment Number | Source* | Gridpoint(s) transposed to ∇ | Critical Duration(s) (hrs) | Obs. Depth (in.) | Controlling for grid point(s) | Total storm adjustment (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/2-4,1927 | 67 | Kinsman Notch | NH | 44°03 | 71°45 | NA1-17 | STR | 16,17,18 | 6 | 7.8 | 16,18 | 141 |
| | | | | | | | | | 24 | 12.0 | | |
| | | | | | | | | | 72 | 14.0 | | |
| 11/15-17,1928 | 68 | Iola | KS | 37°55 | 95°26 | MR3-20 | STR | 6,7,10,11,15 | 24 | 9.0 | 6 | 111 |
| | | | | | | | | | | | 10 | 122 |
| 11/22-25,1940 | 69 | Hempstead | TX | 30°08 | 96°08 | GM5-13 | STR | 7,8,11,12 | 24 | 18.6 | 7 | 100 |
| | | | | | | | | | 72 | 21.1 | | |
| 11/1, 1969 | 70 | Fernandina Bch | FL | 30°41 | 81°28 | | DTD | 15,17 | | | | |
| 12/5-8, 1935 | 72 | Satsuma | TX | 29°54 | 95°37 | GM5-4 | STR | 8,12,15 | 24 | 18.6 | 8,12,15 | 150 |
| | | | | | | | | | 72 | 20.8 | | |
| 12/29-1/1/49 | 73 | Berlin | NY | 42°40 | 73°19 | | STR | 18 | 6 | 3.5 | 18 | 150 |
| | | | | | | | | | 24 | 8.1 | | |
| | | | | | | | | | 72 | 12.6 | | |
| 12/27, 1969 | 74 | Mt.Washington | NH | 44°16 | 71°18 | | DTD | a | | | | |
| 12/10, 1971 | 75 | Vallient | OK | 34°00 | 95°06 | | DTD | 7,11 | | | | |

NOTES:

1.  CoE:  Corps of Engineers

*   Source (refer to table 1)

    STR:  Storm Rainfall

    T.P. 16:  Technical Paper No. 16

    DTH:  Data tape; hourly precipitation

    DTD:  Data tape, daily precipitation

**:  Distance-from coast adjustment used.

∇   See figure 1 for grid point locations
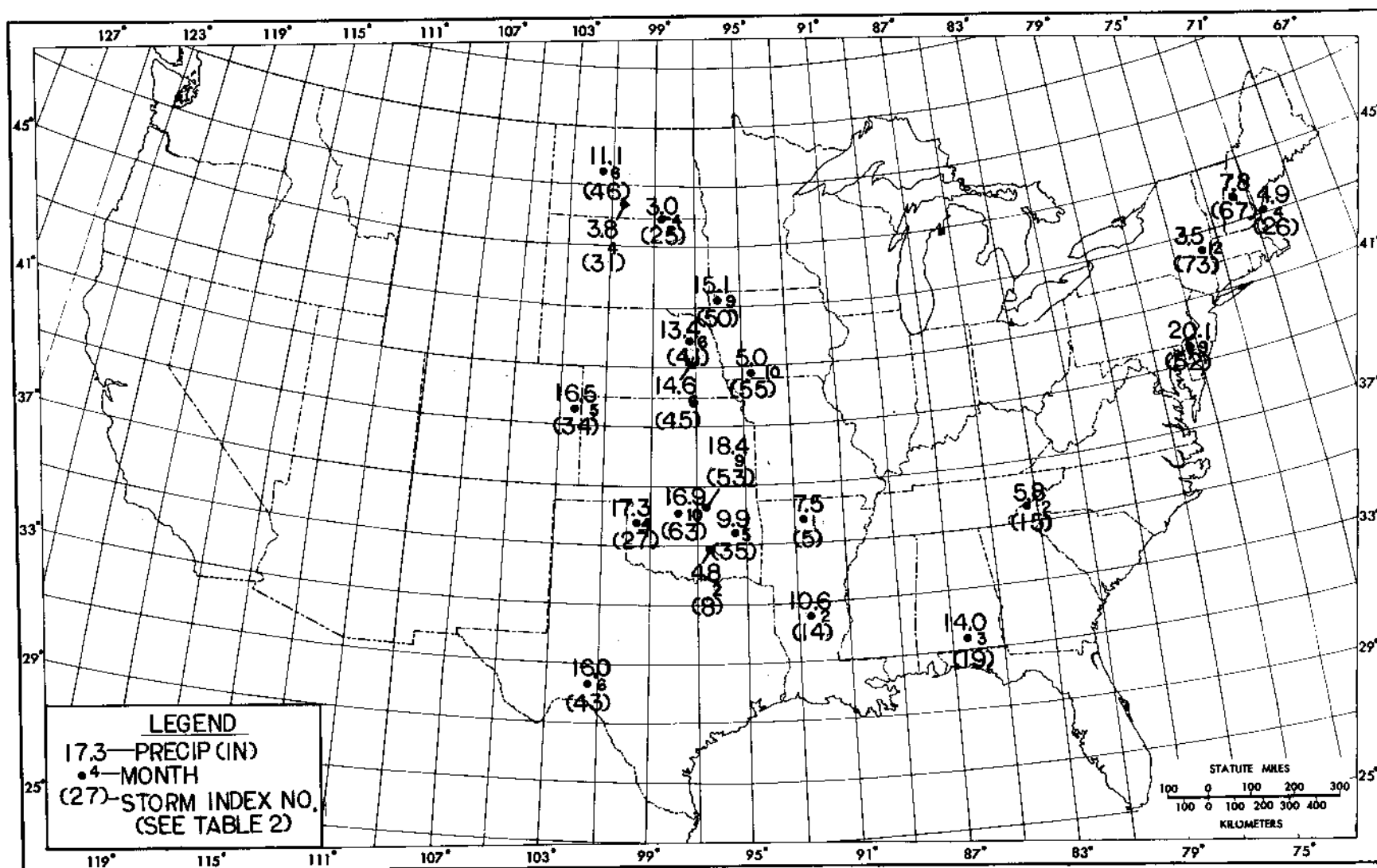
a:   not transposed (see par. 7.2)

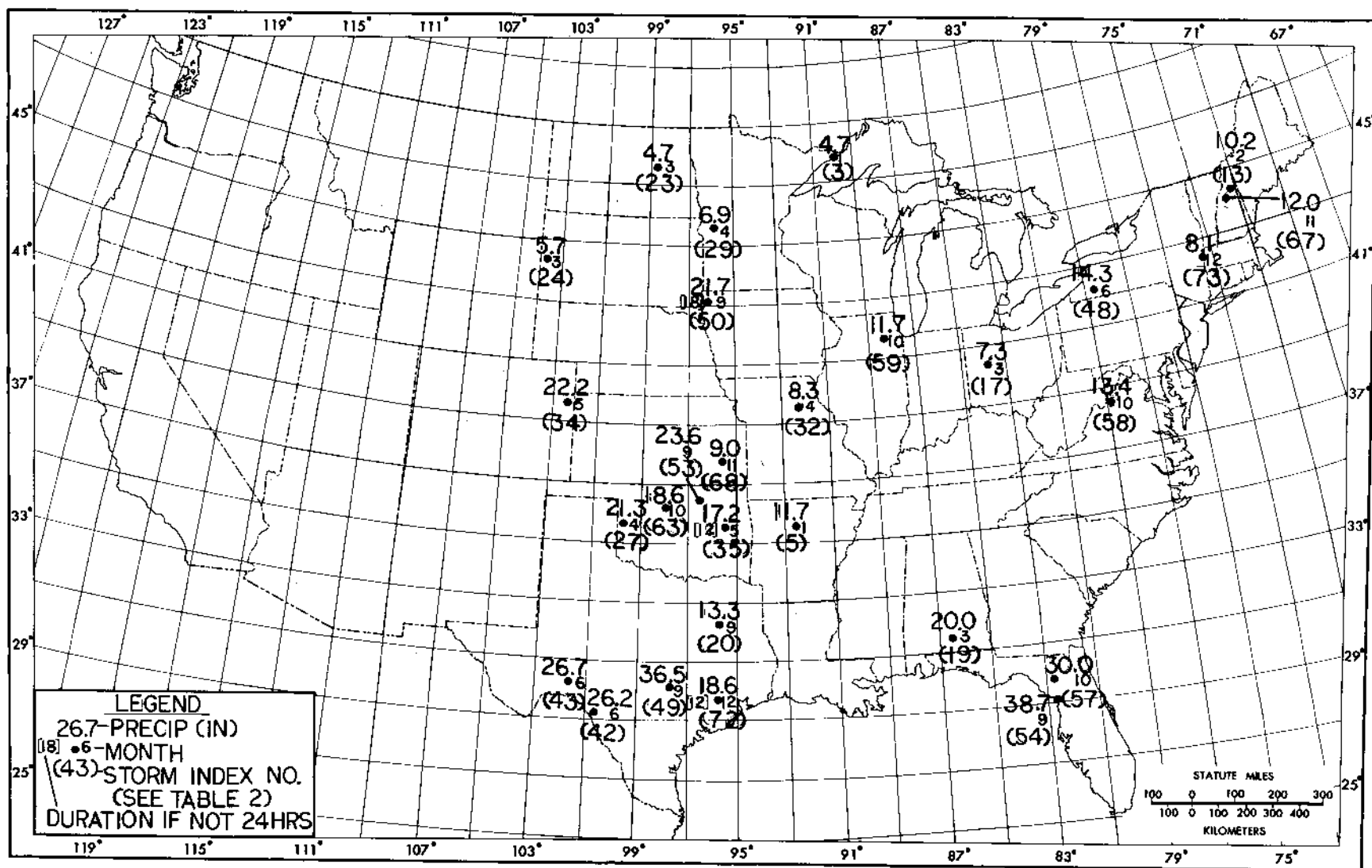*Figure 1a.--Storms controlling PMP (September through June) for 6 hours.*

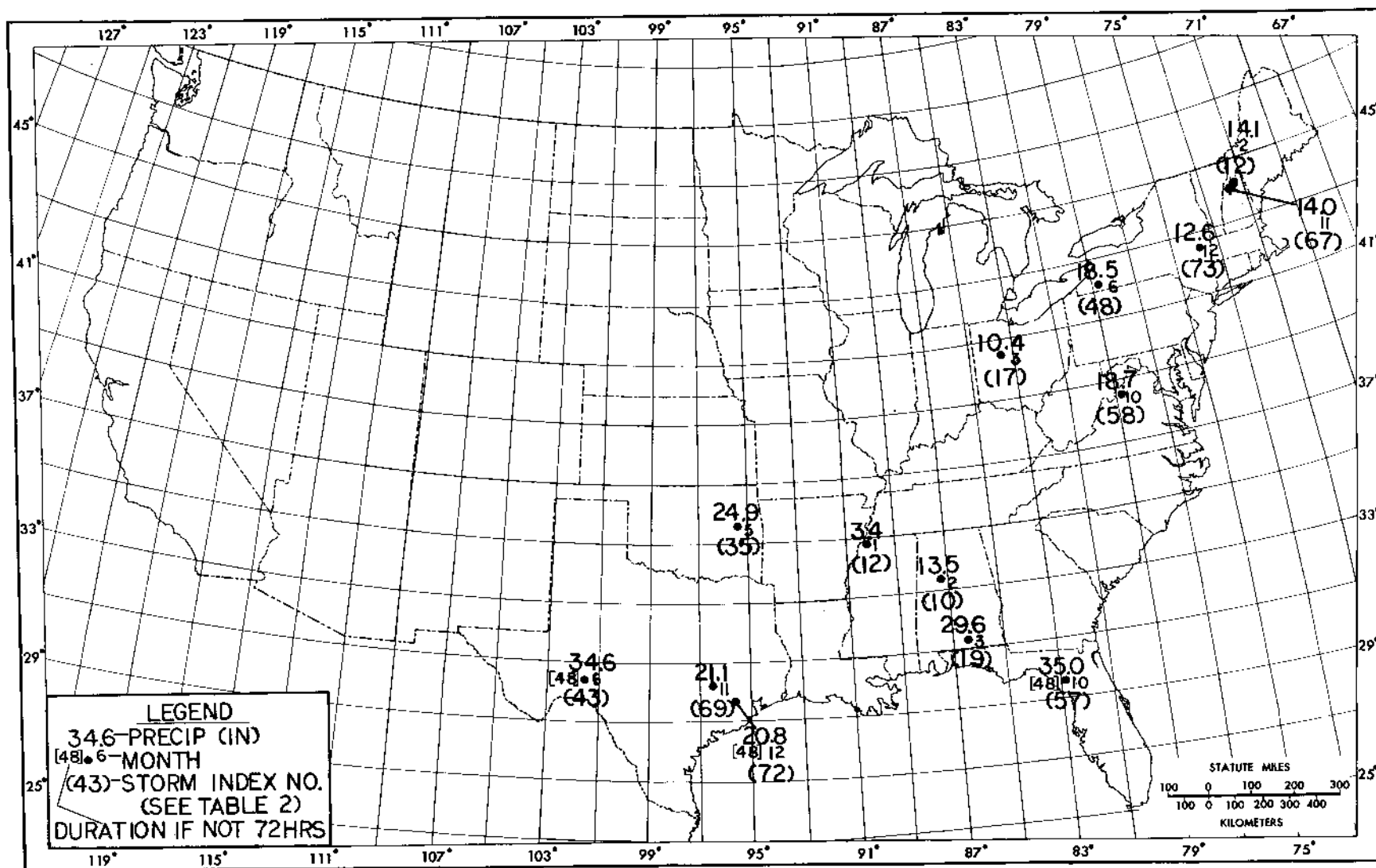*Figure 1b.—Storms controlling PMP (September through June) for 24 hours.*

Figure 1c.--Storms controlling PMP (September through June) for 72 hours.

LEGEND
34.6-PRECIP (IN)
[48]•6-MONTH
(43)-STORM INDEX NO.
(SEE TABLE 2)
DURATION IF NOT 72HRS

*Table 3.--Important storms centered in Canada near the U.S. border*

| Date | Storm no. | Location | | | | Critical duration(s) (hr) | Rainfall depth (in.) |
|------|-----------|----------|--|--|--|---------------------------|----------------------|
|      |           | City | Province | Lat. | Long. | | |
| 1/15-17,1958 | 76 | Liverpool | NS | 44°08 | 64°56 | 24 | 5.8 |
|              |    |           |    |       |       | 60 | 10.0 |
| 3/31-4/2,1962 | 77 | Alma | NB | 45°36 | 64°57 | 24 | 9.3 |
| 5/25-28,1961 | 78 | -- | -- | 45°47 | 66°45 | 6 | 4.0 |
|              |    |    |    |       |       | 24 | 9.5 |
|              |    |    |    |       |       | 72 | 11.8 |
| 5/30,1961 | 79 | Buffalo Gap | Sask. | 49°07 | 105°17 | 6 | 10.5 |
| 6/29-7/1,1935 | 80 | Tilson | Man. | 49°22 | 101°18 | 60 | 13.0 |
| 9/20-23,1942 | 81 | Stellarton | NS | 45°34 | 62°39 | 72 | 13.4 |

therefore published (Ho and Riedel 1979) the maximum observed semimonthly precipitable water ($w_p$ or depth of liquid equivalent of the water in a column of air) for more than 100 stations for the period of record. This information was useful guidance. However, radiosonde data alone cannot be used for moisture maximization for several reasons. First, many extreme storms occurred before the radiosonde network was established. Second, the radiosonde network is too sparse to detect narrow tongues of moisture that are important to many storms. The solution was to use surface dew points, which are observed by many stations, as indices to atmospheric moisture. A saturated pseudo-adiabatic atmosphere is assumed, tied to surface dew points, which fixes the moisture and its distribution with height in the atmosphere. Tests have shown that the moisture thus computed is generally an adequate approximation to atmospheric moisture in major storms or for high dew point situations (Miller 1963). For a saturated pseudo-adiabatic atmosphere, tables have been prepared (U.S. Weather Bureau 1951) giving $w_p$ values based on 1000-mb dew points.

Two dew points are required for moisture maximization. One is the dew point representative of moisture inflow during the storm. The other is the maximum dew point for the same location and time of year as the storm. Both storm and maximum dew points are reduced pseudo-adiabatically to 1000 mb to normalize for differences in station elevations.

Both storm and maximum dew points are usually taken as the highest value persisting for 12 hours. Instantaneous extreme dew point measurements may not be representative of inflow moisture over a significant time period. Also, taken over a duration, the effect of possible erroneous instantaneous dew point values is reduced.

### 3.3.3 Representative Storm Dew Point

Dew points are selected in the warm moist airflow into the storm. Both distance and direction of the dew points from the rainfall center are recorded. An average dew point value from several stations is considered to give the best estimate. Care must be used to insure that dew point observations are taken within the moist tongue involved in the heavy precipitation. The time sequence of dew points from each station is reduced to 1000 mb before averaging. After averaging, the highest persisting 12-hr value is selected.

### 3.3.4 Maximum Dew Point

Maximum dew points are generally the highest dew points observed for a given location and time of year. These dew points are based on seasonal and regional envelopes of maximum observed surface dew points that have persisted for 12 hours, reduced to 1000 mb, at many stations (Environmental Data Service 1968).

We adjust the storm to the maximum dew point 15 days from the storm date into the warmer season except for one case, the Hale, Colo., storm of 1935 which was accompanied by unusually cold air judged to be dynamically significant to the rainfall. Moisture maximization adjustments are increased by up to 10 percent by the 15-day seasonal transposition into the warm season. In the cool season (December-February), the 15-day leeway usually does not change the moisture adjustment.

### 3.3.5 Moisture Adjustment

Moisture maximization is accomplished by multiplying observed rainfall by the moisture adjustment, which is the ratio of $w_p$ for the maximum 1000-mb 12-hr persisting dew point to the $w_p$ for the storm 1000-mb 12-hr persisting dew point. Theoretical justification for this adjustment is found in HMR No. 23 (U.S.W.B. 1947). This maximization expressed mathematically is:

$$P \times \frac{w_p \text{ (maximum)}}{w_p \text{ (storm)}} = \text{moisture adjusted rainfall}$$

where

P = observed rainfall

$w_p$ = precipitable water. (Maximum) refers to enveloping highest observed $w_p$ and (storm) refers to the storm $w_p$. (Both dew points are for the same location.)

### 3.3.6 Elevation and Barrier Considerations

Where there is a significant mountain barrier between the moisture source and rain location, or the rain occurs at high elevations, a refinement is sometimes applied to the moisture adjustment. In such cases, mean elevation of the barrier ridge, or elevation of the rainfall rather than the 1000-mb surface, is used as the base of the column of moisture. For the region of

our study, location of representative storm dew points (usually toward a coast and at lower elevations) and restrictions to storm transposition (par. 3.4.2) generally eliminated the need for using elevation in the moisture adjustment.

## 3.4 Transposition

### 3.4.1 Definition

Transposition means relocating storm precipitation within a region that is homogeneous relative to pertinent terrain and meteorological features.

### 3.4.2 Transposition Limits

Topography is one of the more important controls on limits to how far storms can be transposed. If observed rainfall patterns show correspondence with underlying terrain features, or indicate triggering of rainfall by slopes, transposition should be limited to areas of similar terrain. Identification of broadscale meteorological features is important, e.g., surface and upper air high- and low-pressure centers that are associated with the storm, and how they interact to produce the rainfall. Thus, useful guidance to determining transposition limits are storm isohyetal charts, weather maps, storm tracks, rainfalls of record for the type of storm under consideration, and topographic charts.

The more important limits to storm transposition for this study were:

a. Transposition was not permitted across the generalized Appalachian Mountain ridge.

b. Tropical storm rainfalls were not transposed farther away from nor closer to the coast without an additional adjustment (par. 3.4.4) in cases where the maximum dew point charts showed no variation.

c. In regions of large elevation differences, transpositions were restricted to a narrow elevation band (usually within 1000 feet of the elevation of the storm center).

d. Eastward limits of transposition of storms located in the Central United States were the first major western upslopes of the Appalachians.

e. Westward transposition limits of storms located in Central United States were related to elevation. This varied from storm to storm but in most cases the 3000- or 4000-ft contour was used to set the limit.

f. Southward limits to transposition were generally not defined since other storms located farther south usually provided higher rainfall values.

g. Northward limits were not defined if they extended beyond the Canadian border (the limit of the study region).

We used a simplification in transposing by making decisions for each critical storm on whether or not to transpose to each of 20 grid points

covering the study region. These points are shown on figure 2. A similar set of points was used as a test in the all-season study (HMR No. 51) for transposition rather than setting outer bounds. After regional smoothing, thus extending the influence of major storms, the results of the two techniques are similar for the area size of this study.

## 3.4.3 Transposition Adjustment

The transposition adjustment applied to relocated rainfall values is the ratio of $w_p$ for the maximum 12-hr persisting dew point for the transposed location to that of the storm in place. The maximum dew point is for the same distance and direction from the transposed location as the storm representative dew point is from the storm location (par. 3.3.3).

## 3.4.4 Distance-From-Coast Adjustment for Tropical Storm Rainfall

The general decrease in tropical storm rainfall with distance inland is well known. It is attributed to the difficulty of maintaining the same rainfall intensity as distance from the moisture source increases, and to the deterioration of the tropical storm circulation with increasing distance inland.

A study (Schwarz 1965) developed a relation showing the distance in tropical rainfall with distance up to 300 n.mi. inland. The relation was based on both observed and moisture-maximized tropical rainfall data for several area sizes and durations. Figure 3 shows this variation along with its extension for distance farther inland. It shows no decrease in rainfall for the first 50 n.mi. inland from the gulf coast, a smooth decrease to 80 percent at 205 n.mi. inland, and 55 percent at 400 n.mi. inland.

We applied the adjustment for distance-from-coast to tropical storm rainfall (all durations) transposed within the region where the maximum 12-hr persisting dew point charts (Environmental Data Service 1968) indicate no variation. When transposing tropical storm rainfalls farther from the coast, the values are decreased. In the same way, they are increased when transposed nearer to the coast.

Of the major rains shown in table 2 we applied the distance-from-coast adjustment to six storms. These storms are identified with a double asterisk by the storm number.

## 3.5 Total Storm Adjustment

Table 2 includes the grid points to which the selected major storm rainfalls were transposed, the grid point where the storm was most important, and the total adjustment to the rainfall for those grid points. This total adjustment is the product of the adjustments for maximum moisture and for storm transposition; the latter was determined either from maximum dew points or from the distance-from-coast relation.
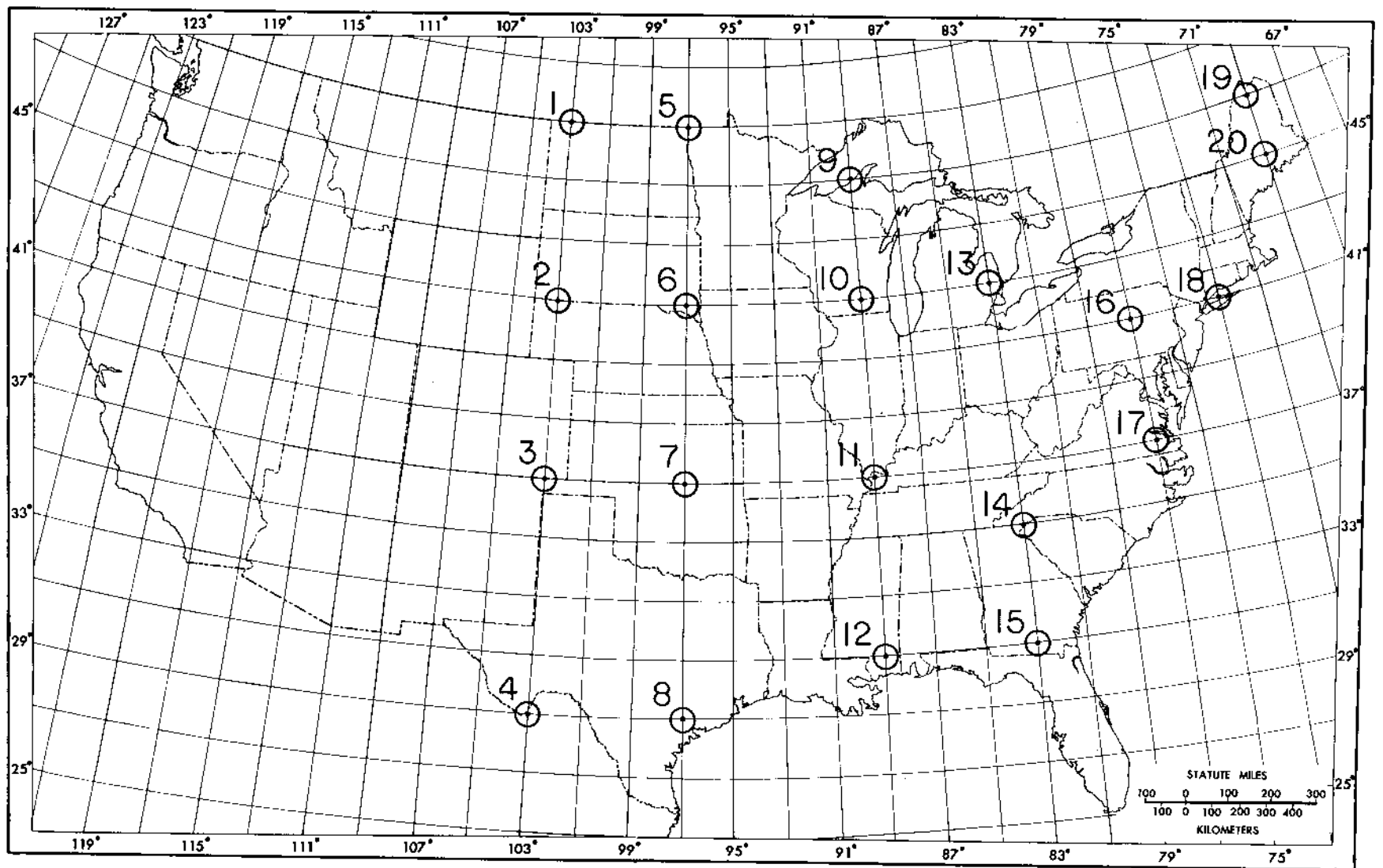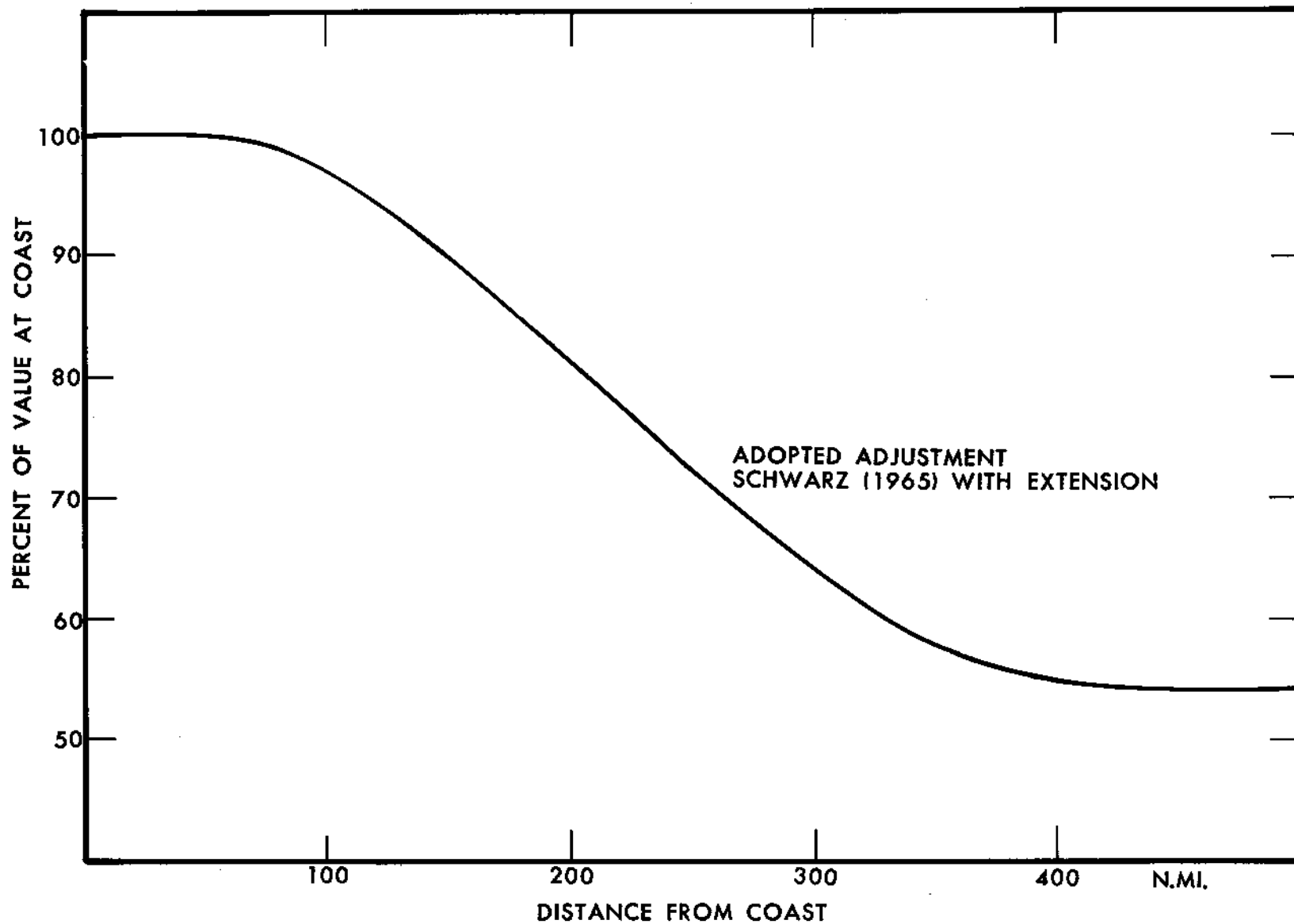
*Figure 2.--Grid points used for transposition.*

Figure 3.--Distance-from-coast adjustment for transposing tropical storm rainfall (from HMR No. 51.).

## 3.6  Envelopment

Moisture maximization and transposition of major storms to the 20 grid points set the very lowest value of PMP for each month at these points. How much to envelop these values and give consistent PMP from place-to-place, month-to-month and duration-to-duration is the major portion of this study.

## 3.6.1  Durationally

By this we mean smooth curves of rainfall depths extending from one duration to another. Such smooth curves imply that the storm record has given more extreme depths for certain selected durations than for others.

## 3.6.2  Seasonally

Seasonal envelopment, in much the same context as in durational envelopment, assumes the storm record does not provide equally extreme depths for all months. We thus draw smooth seasonal curves for a selected grid point, enveloping all of the data for some months.

## 3.6.3  Regionally

We assume that except for topographic and coastal influences we should have a smooth regional pattern of PMP.

# 4.  ANALYSES

## 4.1  Introduction

We have set the stage by describing the available data and the basic concepts that bear on the results and on how these results will be reached. We now give details of the data analyses leading to our goal.

One additional consideration entering into our procedures is how to show results concisely but fully, that is, how to show PMP for durations for 6 to 72 hours for 10 $mi^2$ for each month for the study region. Tests have shown that for a point east of the 105th meridian when PMP values for 6, 24, and 72 hours are plotted on linear graph paper (duration vs. depth) and joined by a smooth curve through the point of origin (0,0) the curve adequately defines PMP by 6-hr increments to 72 hours. We decided to present maps covering the region for each month showing PMP depths at midmonth in inches, for 6, 24, and 72 hours. (For July and August, the mapped values turn out to be identical to the all-season PMP of HMR No. 51 and to each other for the entire study region. Similarly, the PMP values for January and February are the same).

In our approach, we need to take care that the smoothing procedures give PMP values that are not unrealistically extreme: each smoothing step, if not done with care, could give a cumulative envelopment that results in an unreasonably large final product. This concern must be balanced with the basic need -- that at the least, all known observed rainfall depths maximized for moisture should be enveloped. Further, our results should, to the best of our capability, give extremes that will not be exceeded by future storms.

## 4.2  Minimum PMP at 20 Grid Points

Seasonal plots were made for each of the 20 grid points (fig. 2) of the greatest moisture maximized and transposed from depths for 6, 12, 24, 48, and 72 hours. We then drew tentative smooth enveloping curves for these data for 6, 24 and 72 hours on each plot. An example of these plots and in this case the final smooth enveloping curve is shown in figure 4. The storms on the figure (identified by a number near the X axis) can be identified by storm number in table 2.

The remainder of chapter 4 gives analysis of various rainfall data that was helpful in decisions on how to obtain a consistent set of PMP values for all durations, months, and locations.

## 4.3  Statistical Computations of Taped Rainfall Data (1948-73)

Using computer programs we determined a variety of products that could influence or give guidance to our study. The first simple product, of course, is a tabulation of the greatest observed depths for a specified duration for each month of observation. Such maxima lend themselves to statistical analysis.

From the rainfall for each station recorded on tape with 20 or more years of record, the maximum values for each month for a duration of interest were put into series of all January maxima, all February maxima, etc. To each series we fitted the Fisher-Tippett type I distribution by the Gumbel fitting procedure. This statistical distribution is used almost exclusively by the National Weather Service, for precipitation frequency analysis (Hershfield 1961 and Frederick et al. 1977).

From the fits, the rainfall amounts with 0.04 and 0.01 chance of being equalled or exceeded for each month at each station were abstracted (hereafter referred to as 4 percent and 1 percent probability level rainfalls). These rainfall amounts for all stations located with each 2° latitude and longitude quadrangle were then averaged. This was done for quadrangles overlapping (both in the north-south and east-west direction) by 1° latitude and longitude, respectively. This averaging was a smoothing step.

Table 4 summarizes the statistical analyses for 6, 24, and 72 hours. The sets of 4 percent and 1 percent probability level and maximum values which were computed and plotted on maps using a computer program are indicated in table 4, part 1. Figure 5a is an example of the 6-hr 4 percent probability level values for November and their analyses.

Part 2 of table 4 refers to maps of the ratios of monthly values to the maximum value for any one of the 12 months. These ratios are guides to the corresponding ratio of monthly PMP to all-season PMP. Figure 5b is an analyzed example of these ratio maps for the 4 percent probability level amounts for 6 hours for November. The values shown in this figure came from combining the ratios in each quadrangle for the months of November and December. The highest ratio of the two months was selected and plotted.
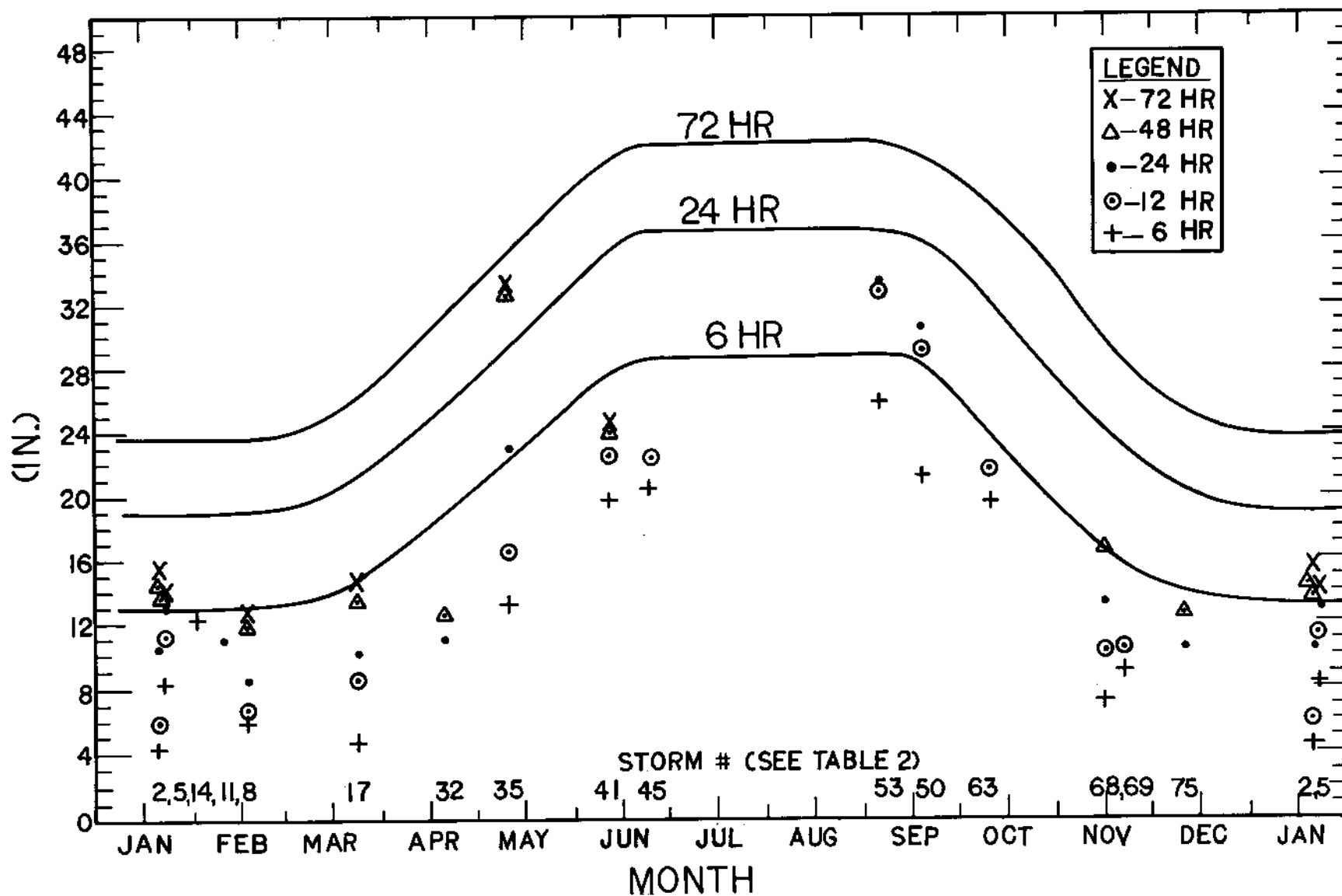
Figure 4.--6-, 24-, and 72-hr PMP for grid point 11, (37°N, 89°W)  Data are moisture maximized and transposed storm rainfall depths.

*Table 4.--Statistical analyses for 1948-73 station precipitation on magnetic tapes*

|  |  | *4% | *1% | maximum |
|---|---|---|---|---|
| **Part 1** | | | | |
| 12 maps,each | 6 hr | X | X | X |
| duration, in | 12 hr | X | X | X |
| inches | 24 hr | X | X | X |
|  | 1 day | X | X | X |
|  | 2 day | X | X | X |
|  | 3 day | X | X | X |
| **Part 2** | | | | |
| 12 maps,each | 6 hr | X | X | X |
| duration,% | 12 hr | X | X | X |
| of highest | 24 hr | X | X | X |
| month | 1 day | X | X | X |
|  | 2 day | X | X | X |
|  | 3 day | X | X | X |
| **Part 3** | | | | |
| 2 maps,each | 6 hr | X | X | X |
| duration of | 12 hr | X | X | X |
| month of | 24 hr | X | X | X |
| maximum and | 1 day | X | X | X |
| and mini- | 2 day | X | X | X |
| mum | 3 day | X | X | X |
| **Part 4** | | | | |
| 12 maps,each | 6/24 | X | X | X |
| rain ratio | 12/24 | X | X | X |
|  | 72/24 | X | X | X |

*4% and 1% probability values based on Fisher-Tippett Type I distribution fitted by the Gumbel procedure.
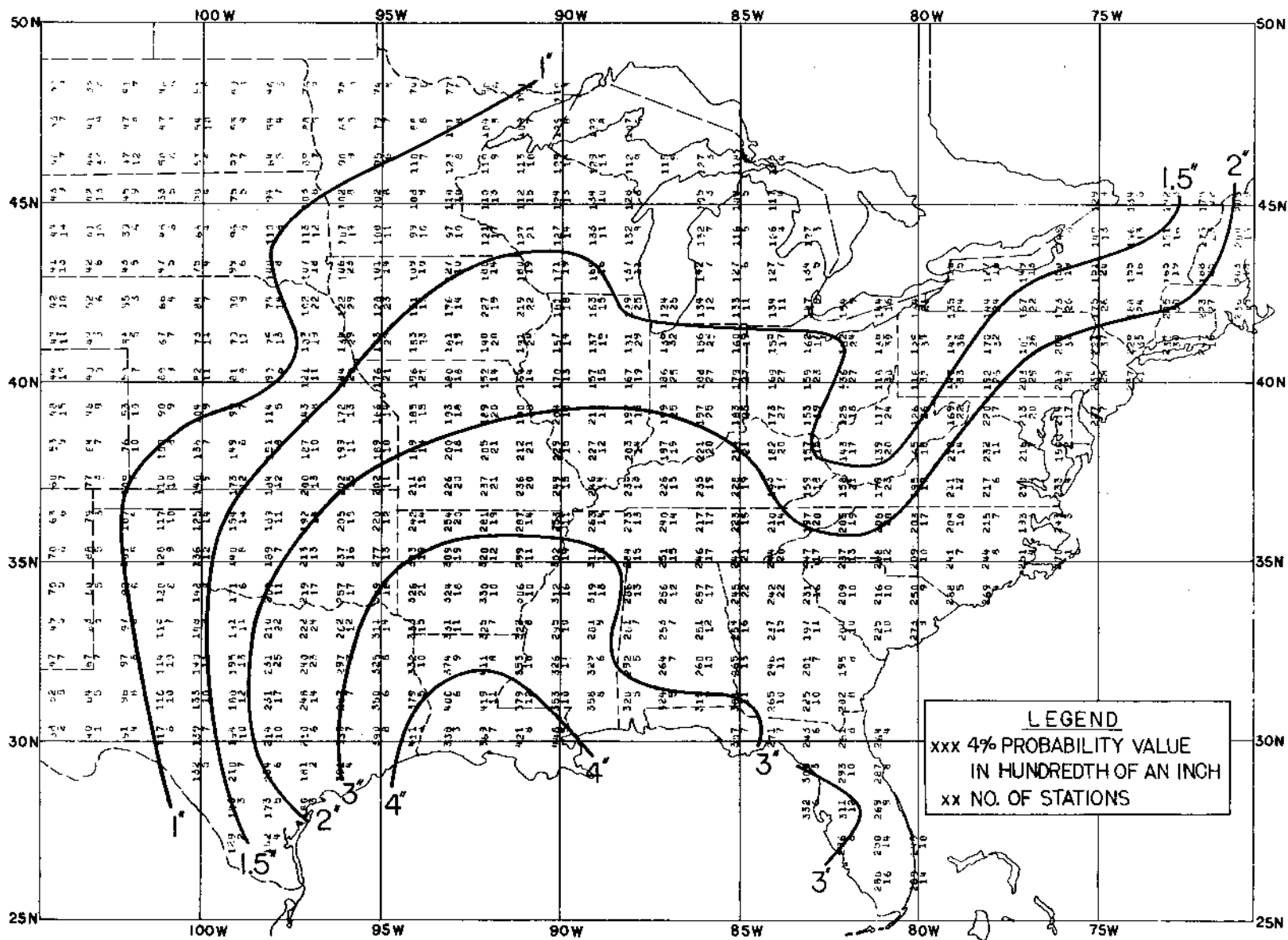
*Figure 5a.--4% probability values for 6-hr duration for November.*
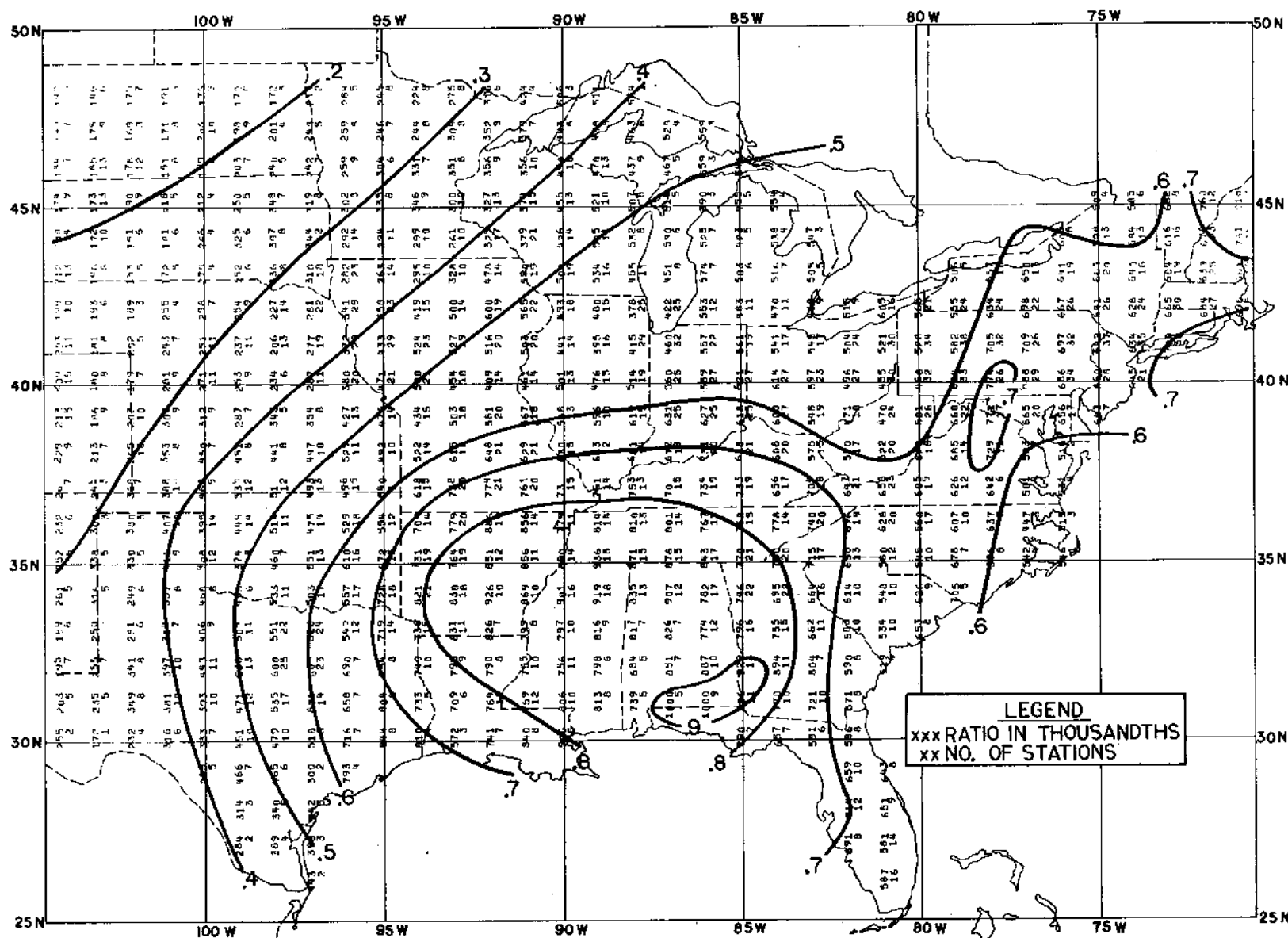
Figure 5b.--Ratios of 4% probability values for 6-hr duration for November or December to the highest of the 12 monthly values.
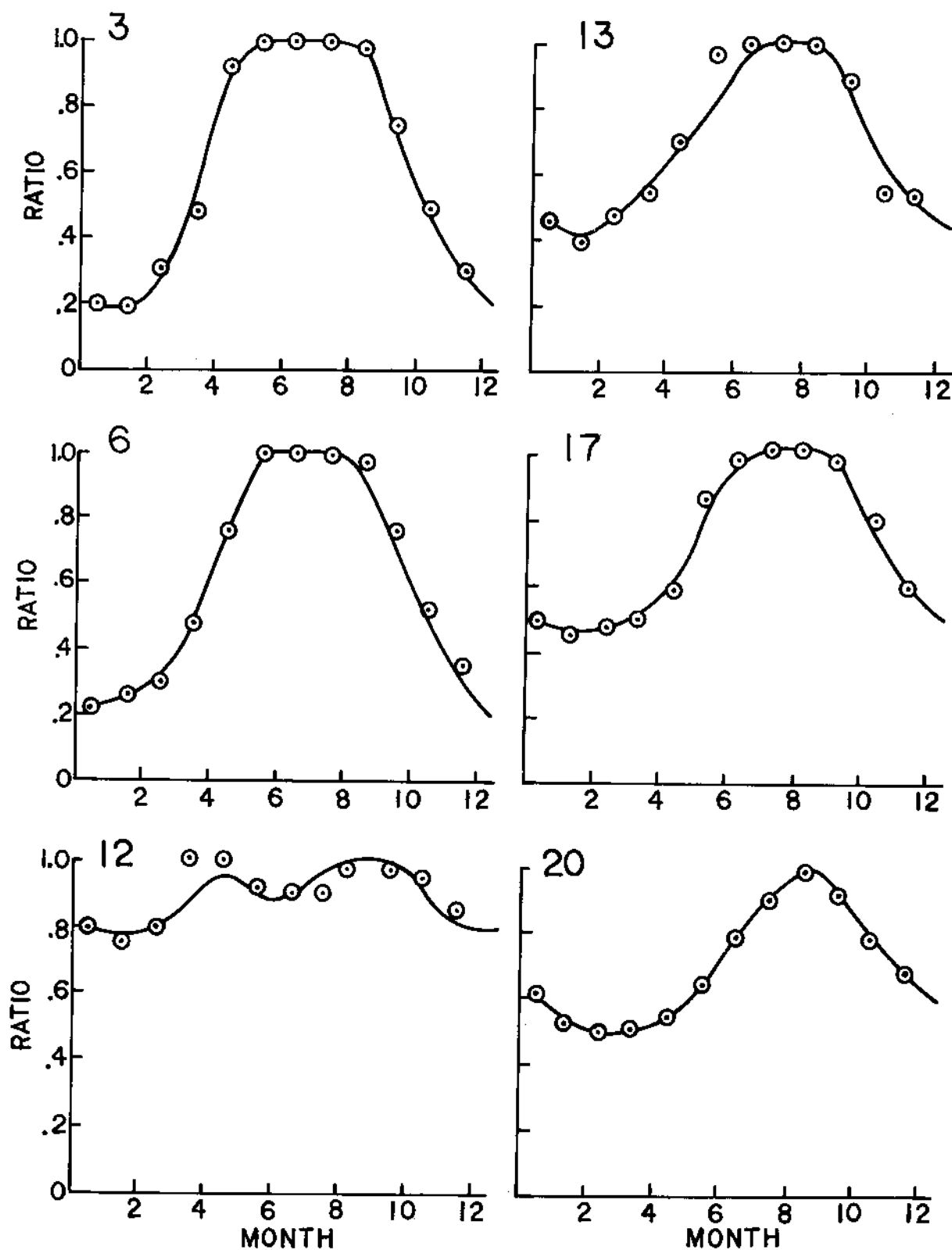
Figure 5c.--Seasonal variation of ratios of monthly maxima to the highest monthly 4% probability values for 6-hr duration (grid points 3, 6, 12, 13, 17, 20).
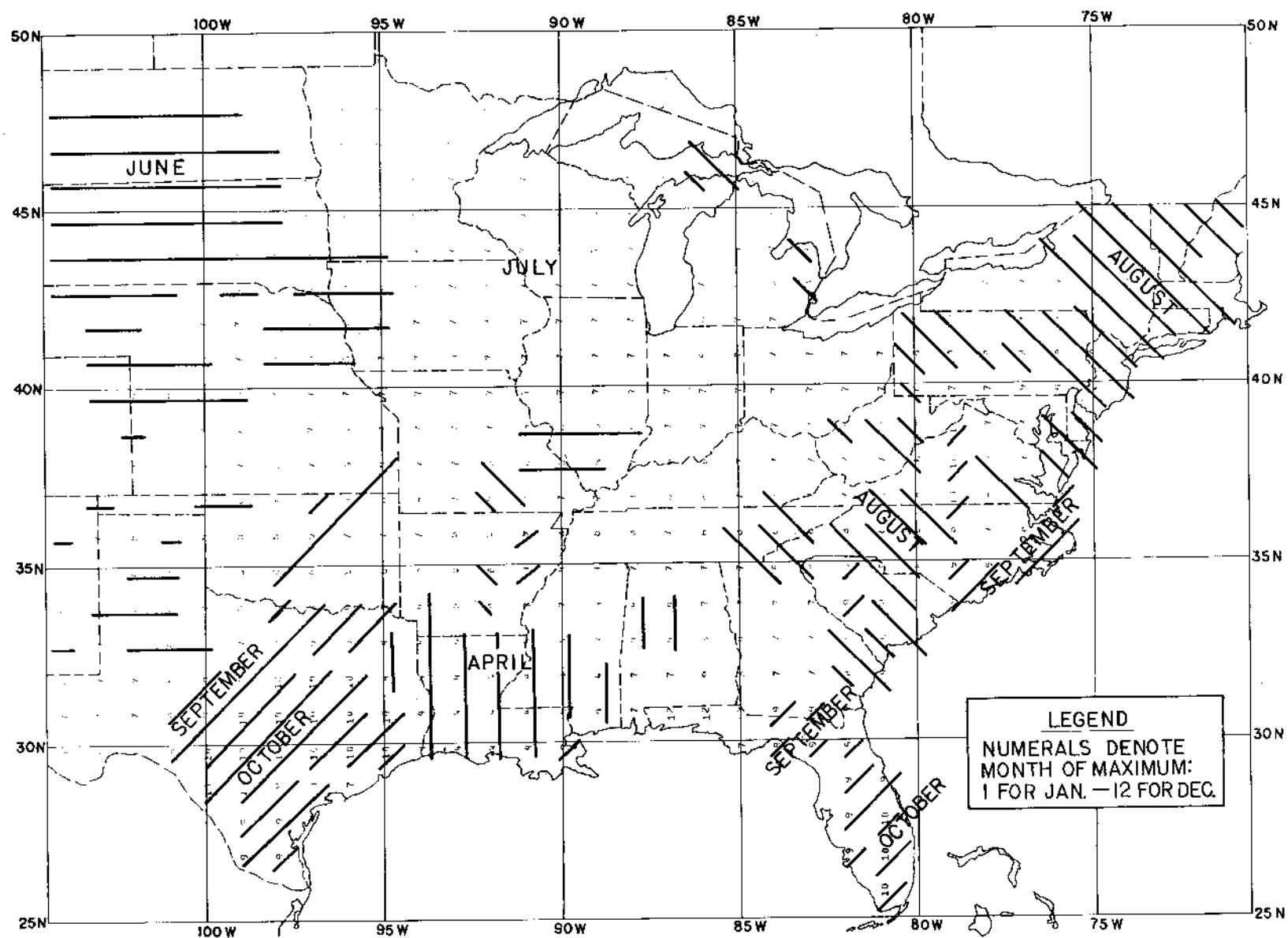
*Figure 5d.—Month of maximum 4% probability values for 6-hours.*

This procedure, applied to all pairs of successive months, was designed to avoid anomalous month-to-month variations.

For the 20 grid points (fig. 2) values were taken from the analyzed ratio maps and plotted on seasonal charts, one for each of the three durations. Figure 5c shows some examples of the results for 6 hours. Equating the highest value to all-season PMP and multiplying this depth by the percents of the maximum, gave us an estimate of PMP for each month based only on the 4 percent probability variation.

The analyzed maps showing the months of maximum and minimum months for the 4 percent, 1 percent and maximum of record levels (part 3 of table 4) also provided helpful information. Figure 5d is an example of the maps showing the month of maximum 4 percent probability level values for the 6-hr duration.

Part 4 of table 3 shows that maps were prepared giving the ratios of 6/24-, 12/24-, and 72/24-hr and 3-day/1-day rains (4 percent, 1 percent, and maximum of record levels). Such ratios are a guide to maintaining depth-durational consistency in the final product.

## 4.4 Maximum Observed Rainfall Values

Under par. 3.2 we discussed maps of maximum rainfall based on all the data sets listed in table 1. Such maps were developed for 6-, 12-, 24-, 48-, and 72-hr durations. Smooth regional analyses were made of data on each of these maps, taking into account in at least a gross manner, the maximum values on adjacent maps so that there would not be unrealistic changes from month to month. This resulted in a few extreme storms being undercut. Of course without moisture maximization and transposition these analyses give values that are too low for PMP. Figures 6a, 6b, and 6c are examples of maps of the extremes with analyses for 6-hr, 24-hr, and 72-hr durations, respectively, for November. These maps show storm depths with numbers in parentheses, in some cases, that correspond to the storm numbers in table 2.

From the map analyses, values were read for the 20 grid points (fig. 2). Smooth seasonal curves were drawn to these monthly maxima for each grid point separately. Another set of monthly curves were developed by expressing each month's depth in percent of the maximum (of the 12 months). The resulting smooth curve is, then, a seasonal variation of percents of the maximum month (100 percent) based only on the analysis of observed data. Figure 6d is an example of the seasonal variation of the ratios for 6-hour rainfall for 6 selected grid points.

## 4.5 Maximum Atmospheric Moisture

## 4.5.1 Precipitable Water in Soundings

Since we adjust record storms to maximum moisture ($w_p$), guidance to our work here is maximum observed moisture at upper-air sounding stations. Such $w_p$ values have been computed for twice-a-day soundings for the period of reliable records for all U.S. stations and the maximum values extracted on a

semimonthly basis (Ho and Riedel 1979). In that publication, such values have also been plotted on maps and analyzed for our study region. These analyses were smoothed seasonally as well as regionally. Figure 7a is an example of such maps taken from that publication.

## 4.5.2 Surface Dew Points

In par. 3.3.4 we briefly described maps of maximum 1000-mb 12-hr persisting dew points ($T_d$). These maps, being an index to moisture in the atmosphere, are also clues to smooth seasonal and regional patterns of extreme rainfall. An example of these maps is shown in figure 7b.

## 4.5.3 Seasonal Variation of Maximum Moisture

We determined the seasonal variation of both maximum $w_p$ and maximum $T_d$ (see figures 7a and 7b for examples) by expressing each month or half-month value as a percent of the highest of the year for each of the 20 grid points. Figure 7c shows examples of these smooth seasonal curves.

## 4.6 Seasonal Variation of Rainfall at Selected Long Record Stations (1912-61)

Daily precipitation amounts of some 50 selected stations with 50 years of record (1912-61) are recorded on magnetic tape. This record was processed in the same way as the 1948-73 tape data (par. 4.3), except that the data were not spatially averaged. Seasonal variations of these computed parameters were plotted for each station separately.

Figure 8 shows the unsmoothed and computer-produced plots for Duluth, Minn., and Kansas City, Mo., for the 3-day duration. For each month, the maximum observed value, the 1 and 4 percent probability values, and the ratio of each month's 4 percent probability value to the maximum monthly value for the year are given.

## 4.7 Rainfall Depth-Duration Relations

### 4.7.1 Within Storm

Depth-duration relations of rainfall in major storms and their variations within the region and seasonally, give guidance to depth-duration relations for PMP. The 6- to 24-hr (6/24) rain ratios together with 72- to 24-hr (72/24) rain ratios quite adequately define depth-duration relations from 6 to 72 hours. We computed these two sets of ratios for the major storms for 6, 24 and 72 hours given in *Storm Rainfall in the United States* for each month. High 6- and high 24-hr depths were both considered for 6/24 ratios in order not to bias the results. Similar data selection was carried out for the 72/24 ratios. Of course, for the storm to be counted, it had to last at least 24 hours for a 6/24 ratio and 72 hours for a 72/24 ratio.
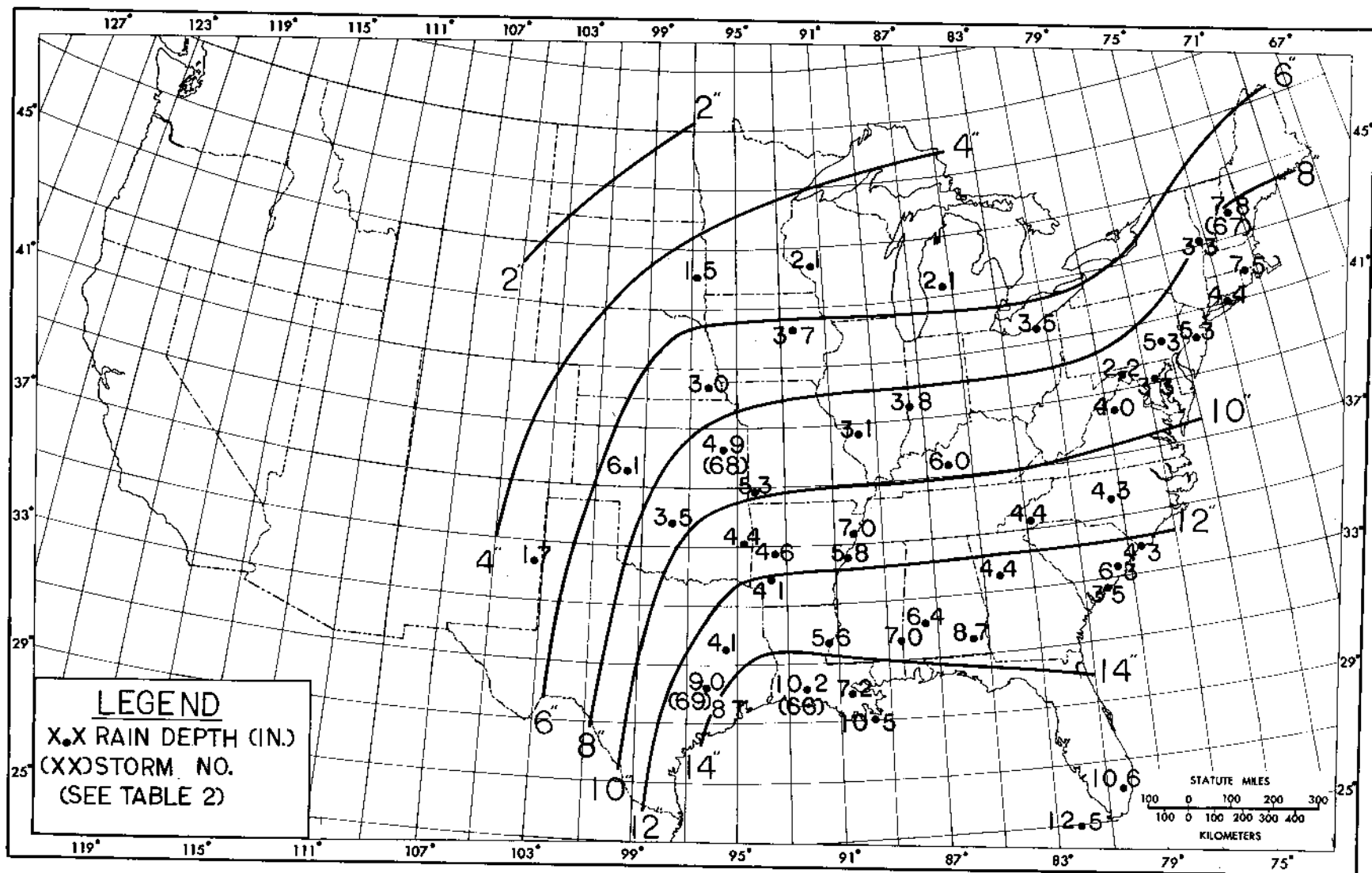
*Figure 6a.--Example of analyzed maps of greatest observed 6-hr rainfall (November).*
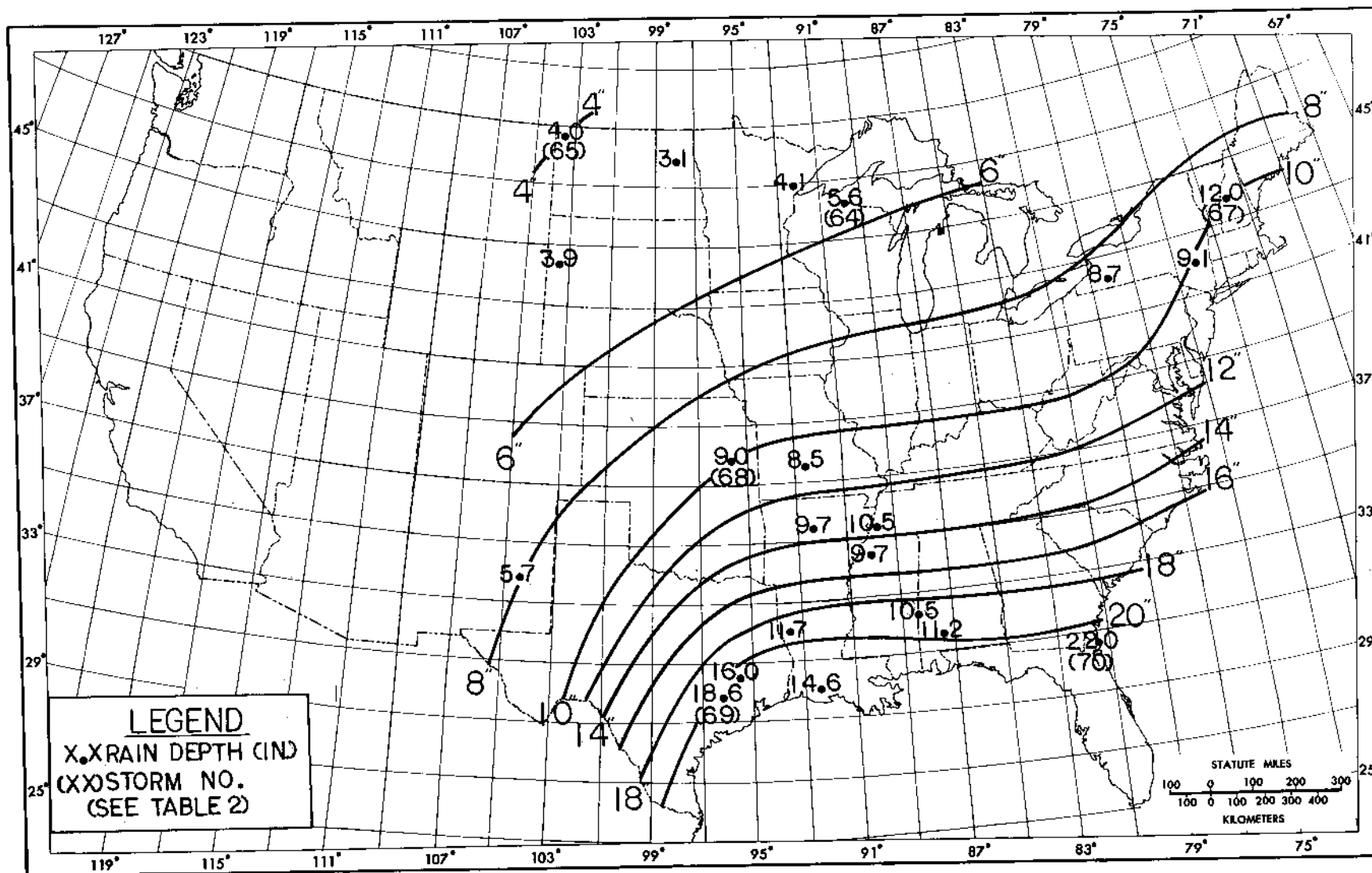
*Figure 6b.--Example of analyzed maps of greatest observed 24-hr rainfall (November).*
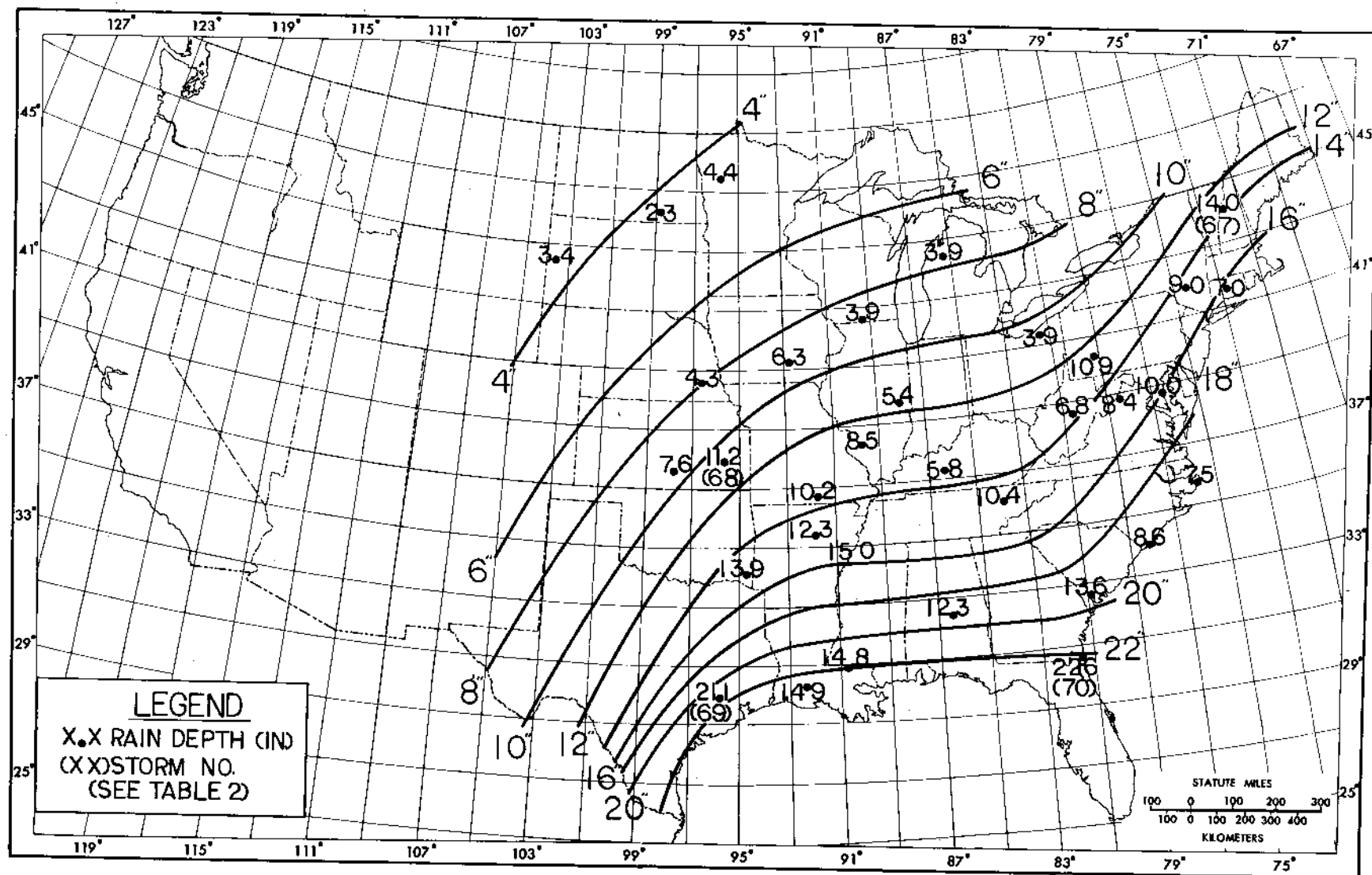
Figure 6c.--Example of analyzed maps of greatest observed 72-hr rainfall (November).
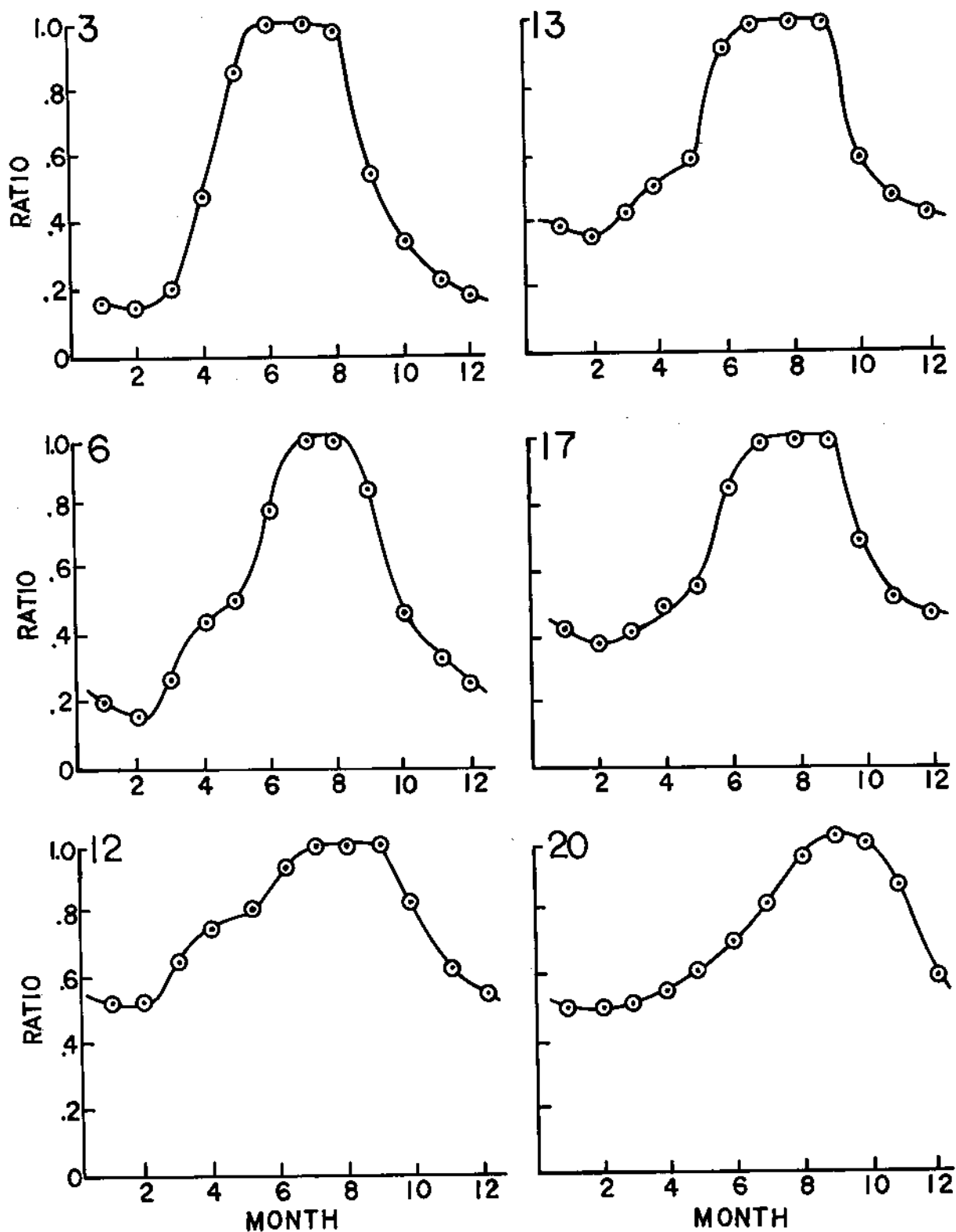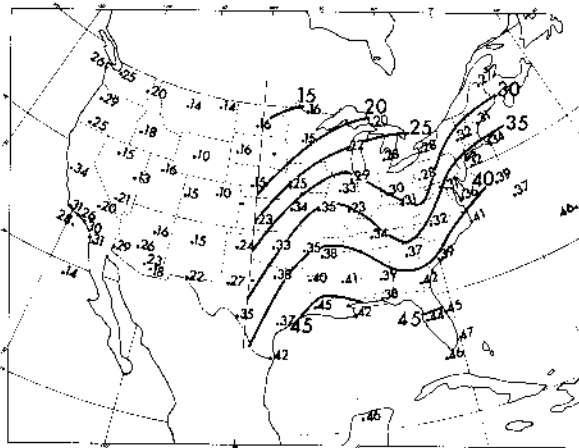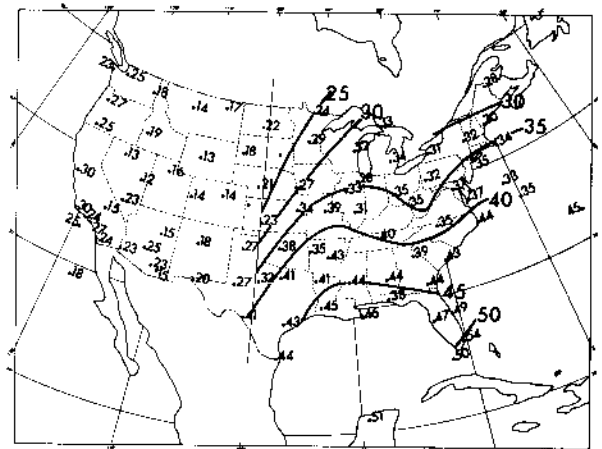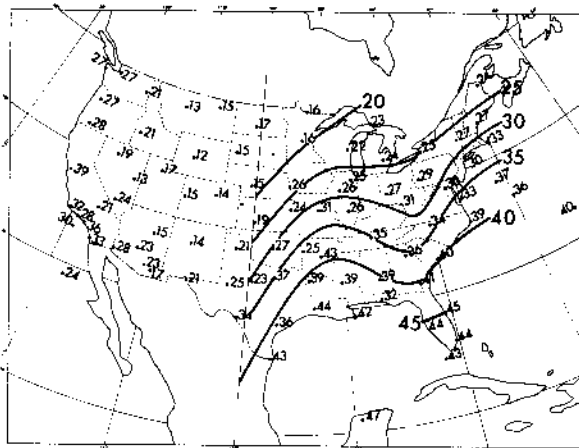
*Figure 6d.—Seasonal variation of ratios of monthly maxima to the highest monthly maxima for maximum observed 6-hr rainfall (for grid points 3, 6, 12, 13, 17, 10).*
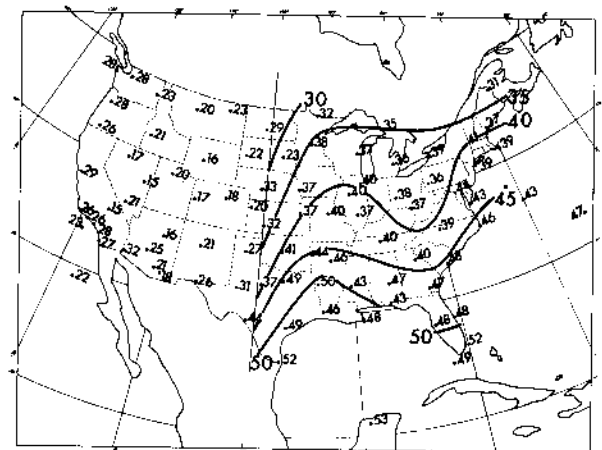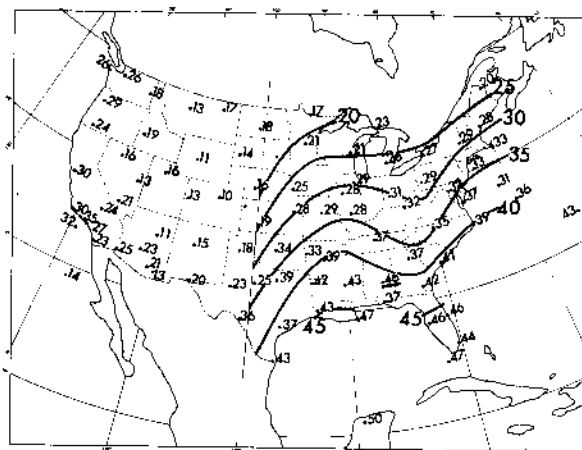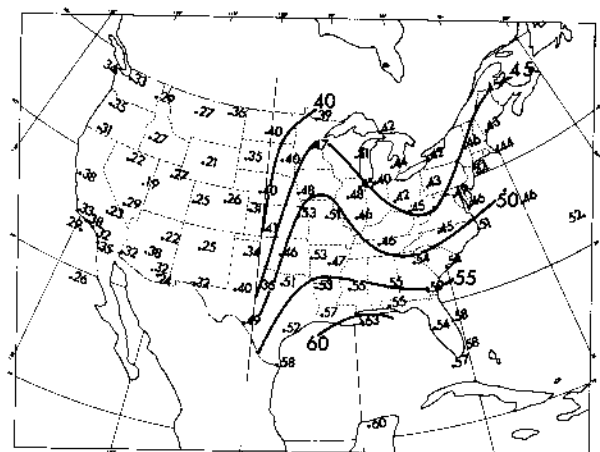
34



January 1-15

April 1-15

February 1-15

May 1-15

March 1-15

June 1-15

Figure 7a.--Contiguous United States, maximum $w_p$ (mm), surface to 500-mb, by half months, January through June (from Ho and Riedel, 1979).
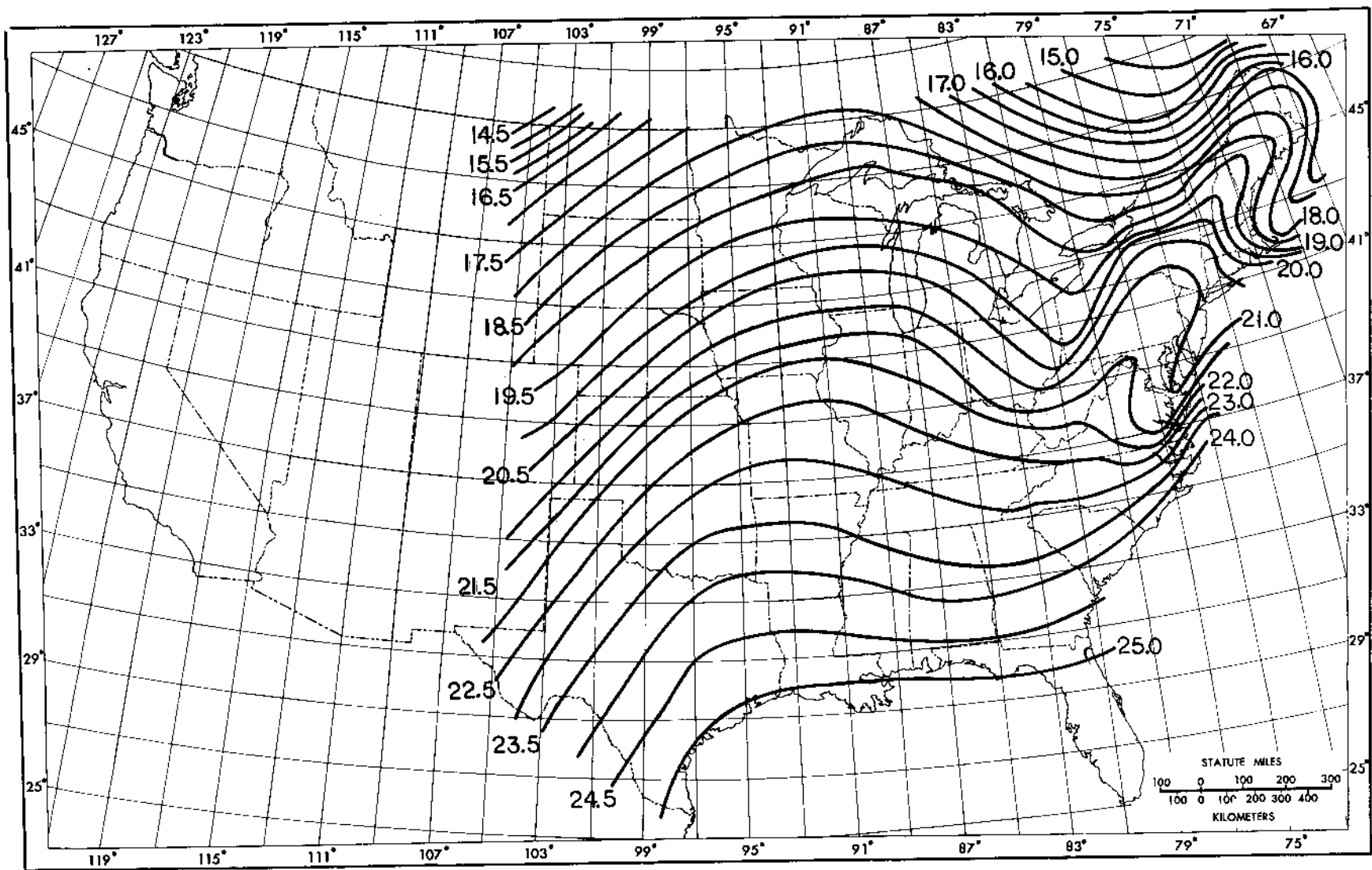
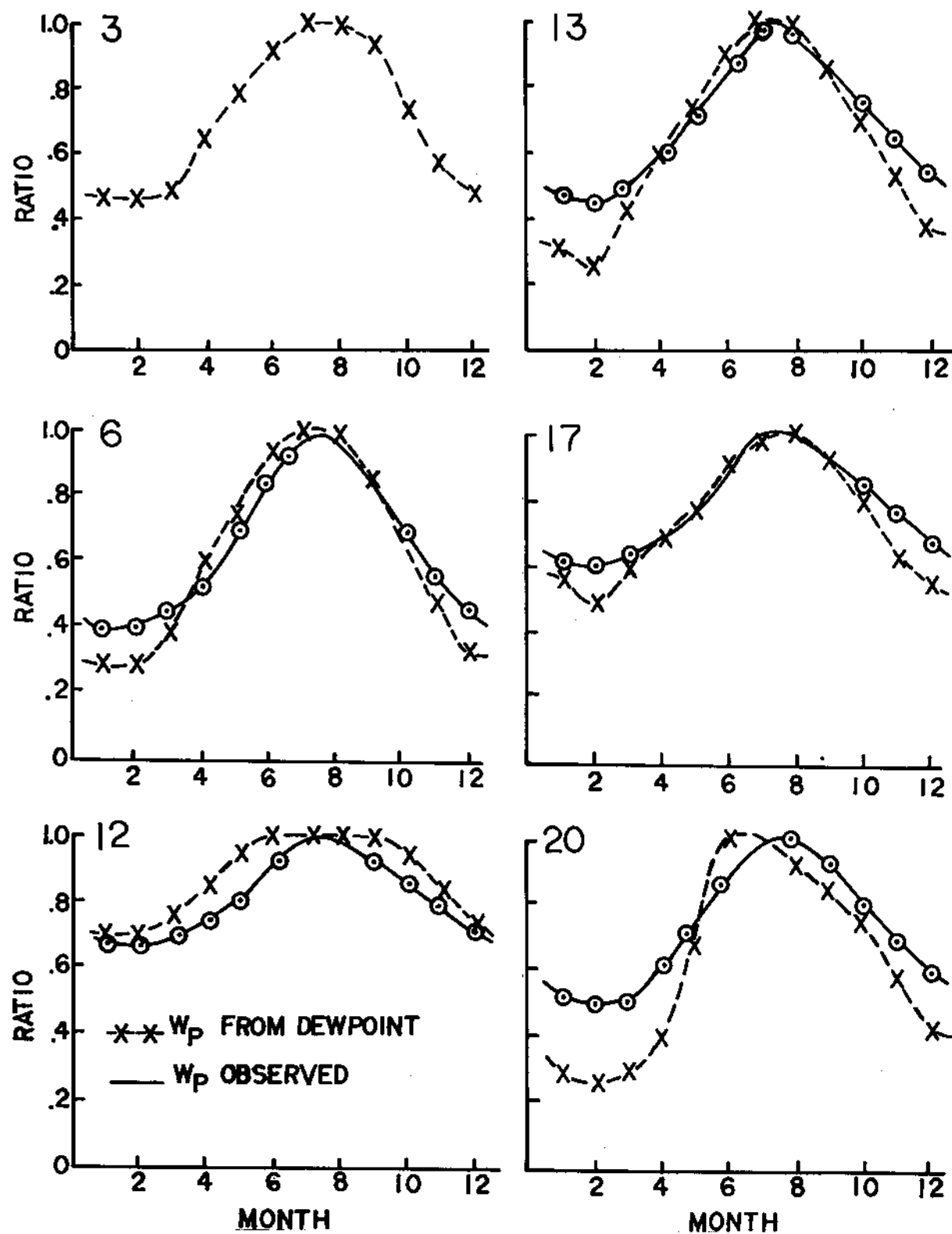*Figure 7b.--Maximum 12-hr persisting 1000-mb dew point (°C) for October (Environmental Data Service, 1968).*

*Figure 7c.--Seasonal variation of ratios of atmospheric moisture for each month to that for the highest month (grid points 3, 6, 12, 13, 17, 20).*
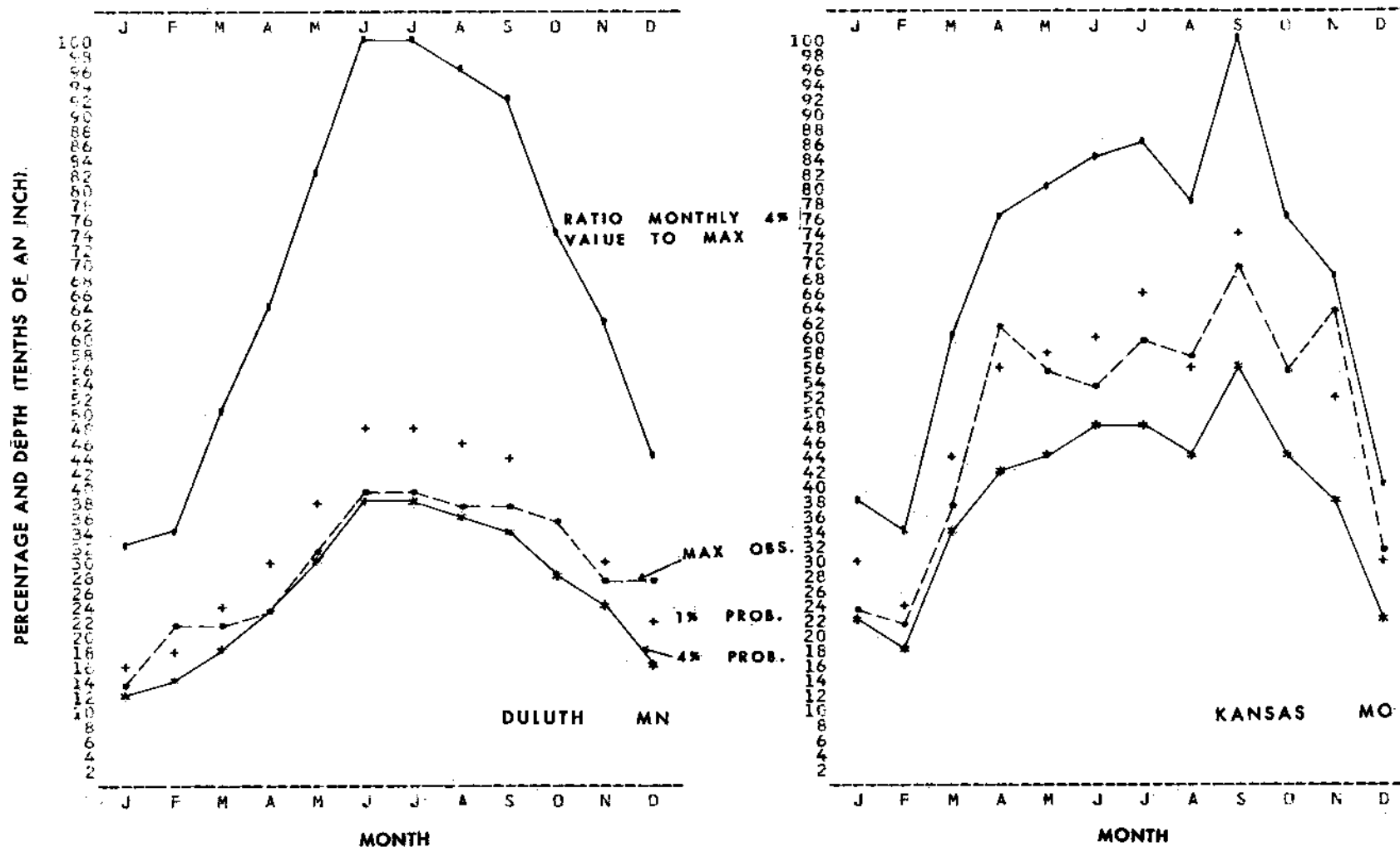
Figure 8.--Example of seasonal variations of 1% and 4% probability value, the maximum of record, and the ratio of each month's 4% probability value to that for the highest month. Three day rainfall for Duluth, Minnesota and Kansas City, Missouri (1912-61)

Figure 9 is a plot of the seasonal variation of the monthly 6/24 ratios for all the qualifying storms. The number of storms making up the averages, from a low of 10 in February to a high of 67 in September, are shown as well as the range in the ratio for each month. A fairly significant seasonal variation is indicated by the averages with generally higher ratios in the warm season. Figures 10a and 10b show maps of the 6/24 ratios for January and July, respectively. The data for January are too scanty to give a meaningful geographical pattern. We have identified certain ratios on the map for July (fig. 10b); those between 0.7 and 0.9 in boxes and those between 0.3 and 0.5 in circles to aid in discerning regional preference or bias in magnitude of the ratios. We conclude from the distributions shown that there is no significant regional pattern in magnitude of the ratios for our sample.

How the 6/24 ratios vary with rainfall magnitude is also of interest to our study. Figure 11 is a plot of the ratio vs. the 24-hr value in each ratio. Varying symbols are used to distinguish the four seasons. While a slight trend is shown in these data toward lower ratios with increasing 24-hr depths, one must be careful in interpreting this since all else being equal, the greater the 24-hr value (the denominator in the ratio) the lower the ratio. We conclude there is no signficant variation of 6/24 ratios with magnitude of the rainfall or season.

Plots were made for 72/24 ratios analogous to those for 6/24 ratios based on the same data base. Averages of these ratios by months (see fig. 12) show a smaller seasonal trend than for 6/24 ratios. Maps of the 72/24 ratios (not shown) give little evidence of regional patterns. As with the 6/24 ratios (see fig. 13) there is no significant trend in the 72/24 ratio with magnitude of the 72-hr rain.

## 4.7.2 Among Storms

Analyses of and compositing maps of the greatest observed rainfalls for 6-, 24-, and 72 hours implicitly sets 6/24 and 72/24 among storm ratios. these, along with the ratios given by HMR No. 51, were useful tools to our study.

## 4.7.3 Analyses

Since 6-, 24-, and 72-hr seasonal curves were plotted for the 20 grid points, the question of spacing between them comes up, that is, compatibility must be maintained in depth-duration relations. We strove for such compatibility through depth-duration plots for each grid point and month. Figure 14 is an example of these plots for 6 selected grid points for the month of November. On here are plotted transposed and moisture-maximized storm depths for all durations from 6 to 72 hours. Such plots insure that our 6-, 24-, and 72-hr PMP will properly envelop maximum depths for other intermediate durations. Storms are identified by number (see table 2). At top of the plots for each grid point we also show rain ratios: 6- to 24-hr and 72- to 24-hr from the PMP and from the 4 percent probability level rainfall (part 4 of table 4). The ratios from rainfall frequencies are a guide to maintaining depth-durational consistency in the final product.

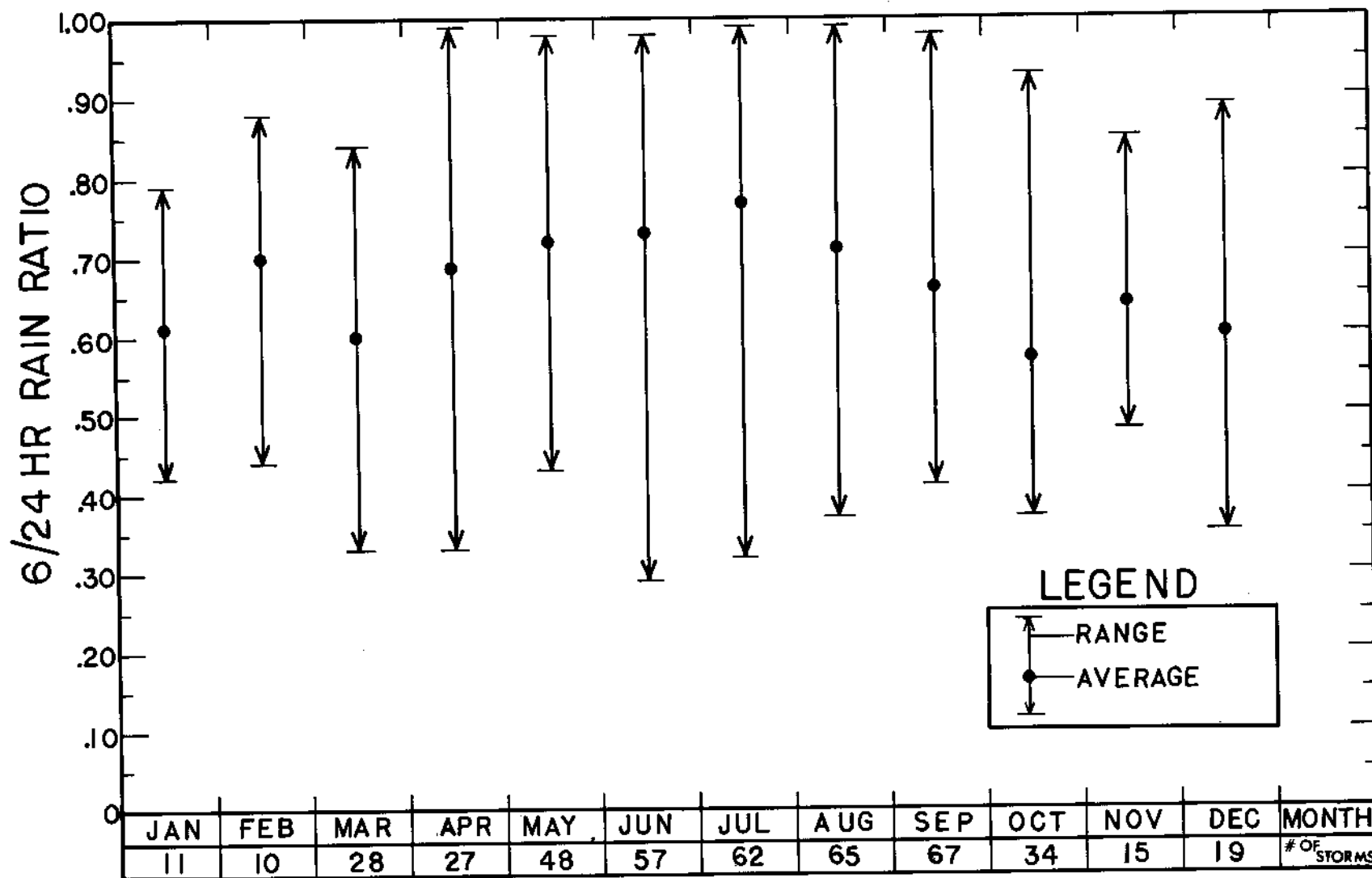| MONTH | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | MONTH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # OF STORMS | 11 | 10 | 28 | 27 | 48 | 57 | 62 | 65 | 67 | 34 | 15 | 19 | # OF STORMS |

LEGEND

RANGE

AVERAGE

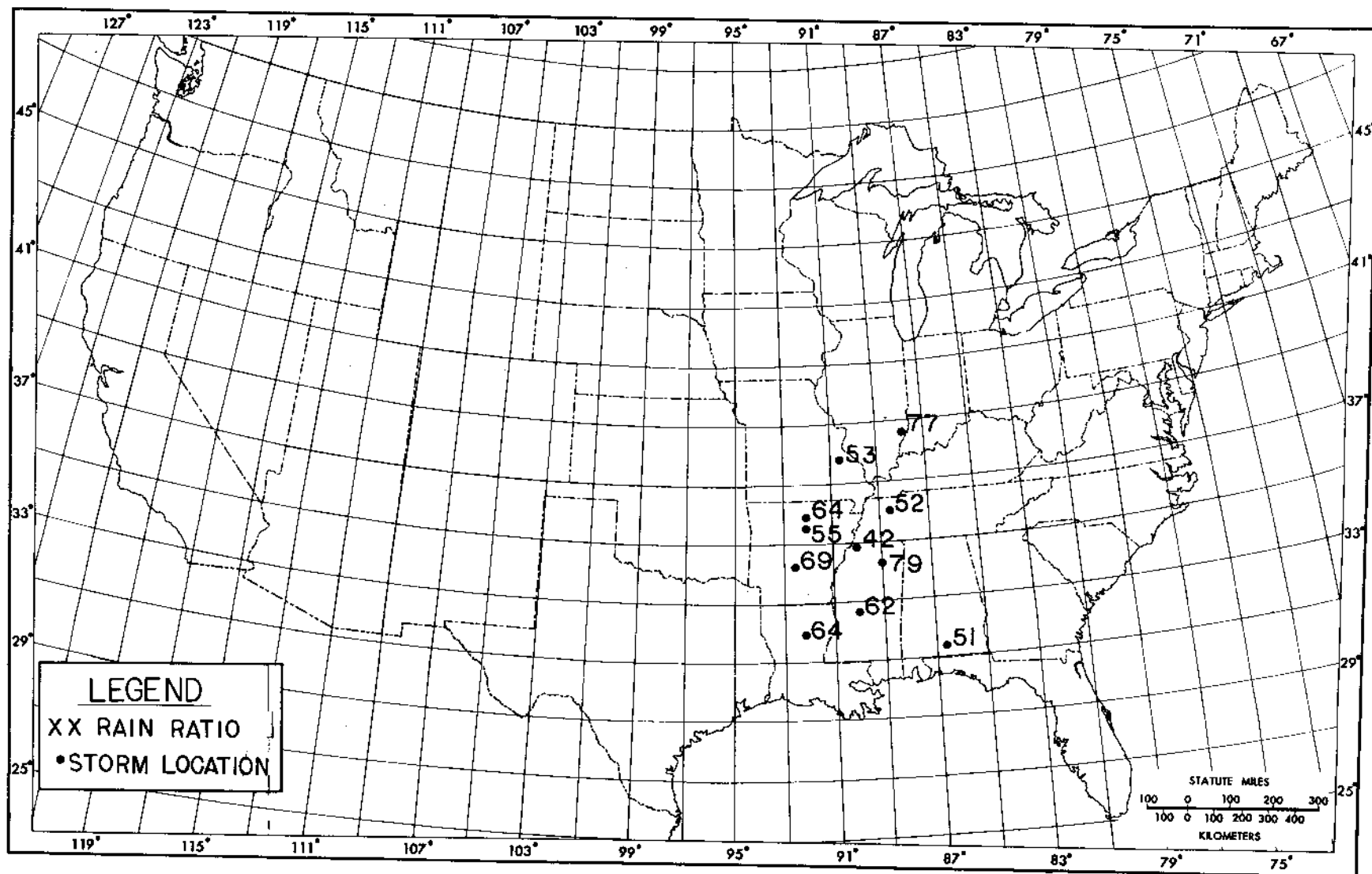Figure 9.--Seasonal variation of within storm 6/24-hr rain ratios for major storms in the study region.
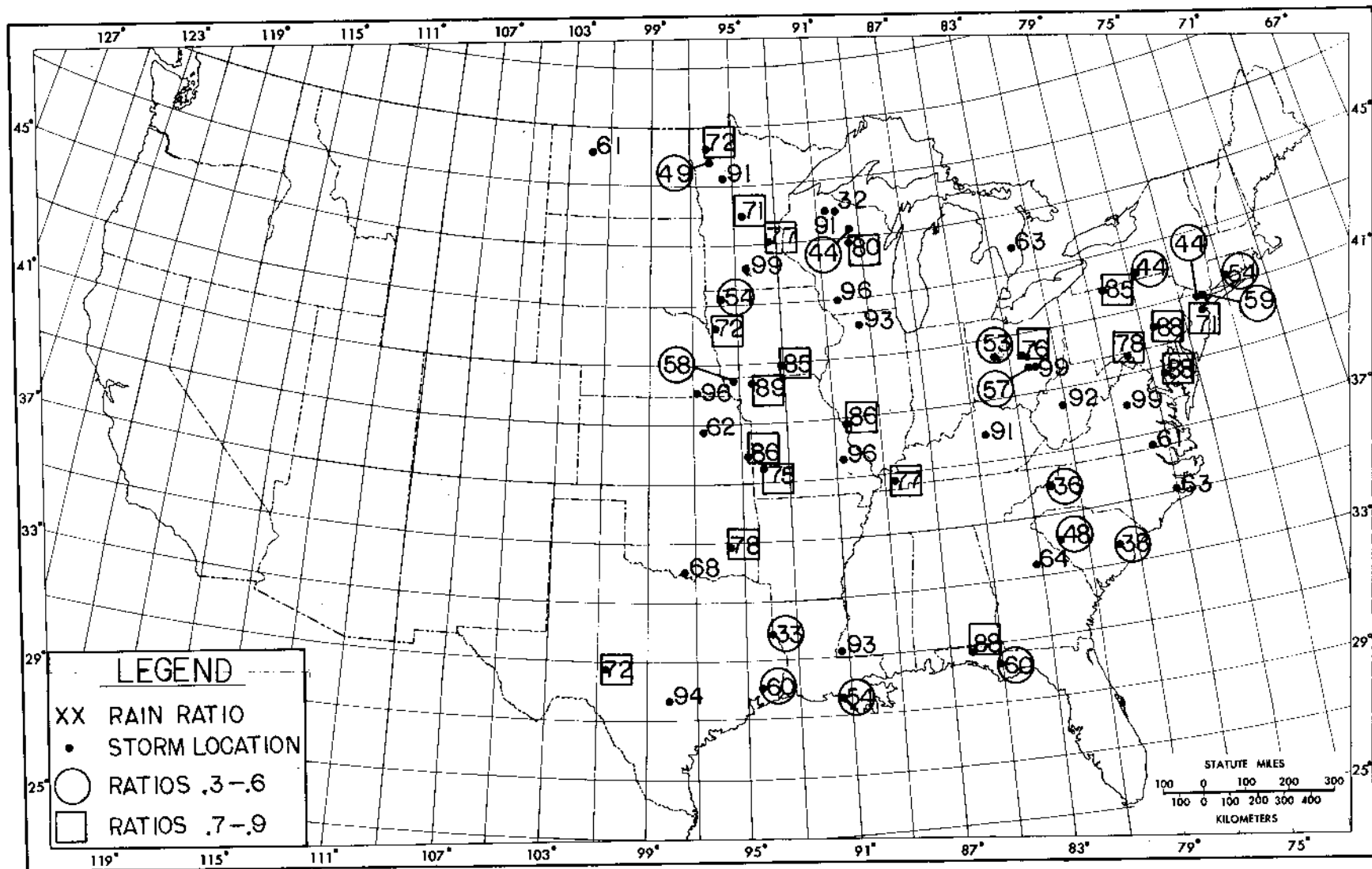
Figure 10a.—Within storm 6/24-hr rain ratios, January.
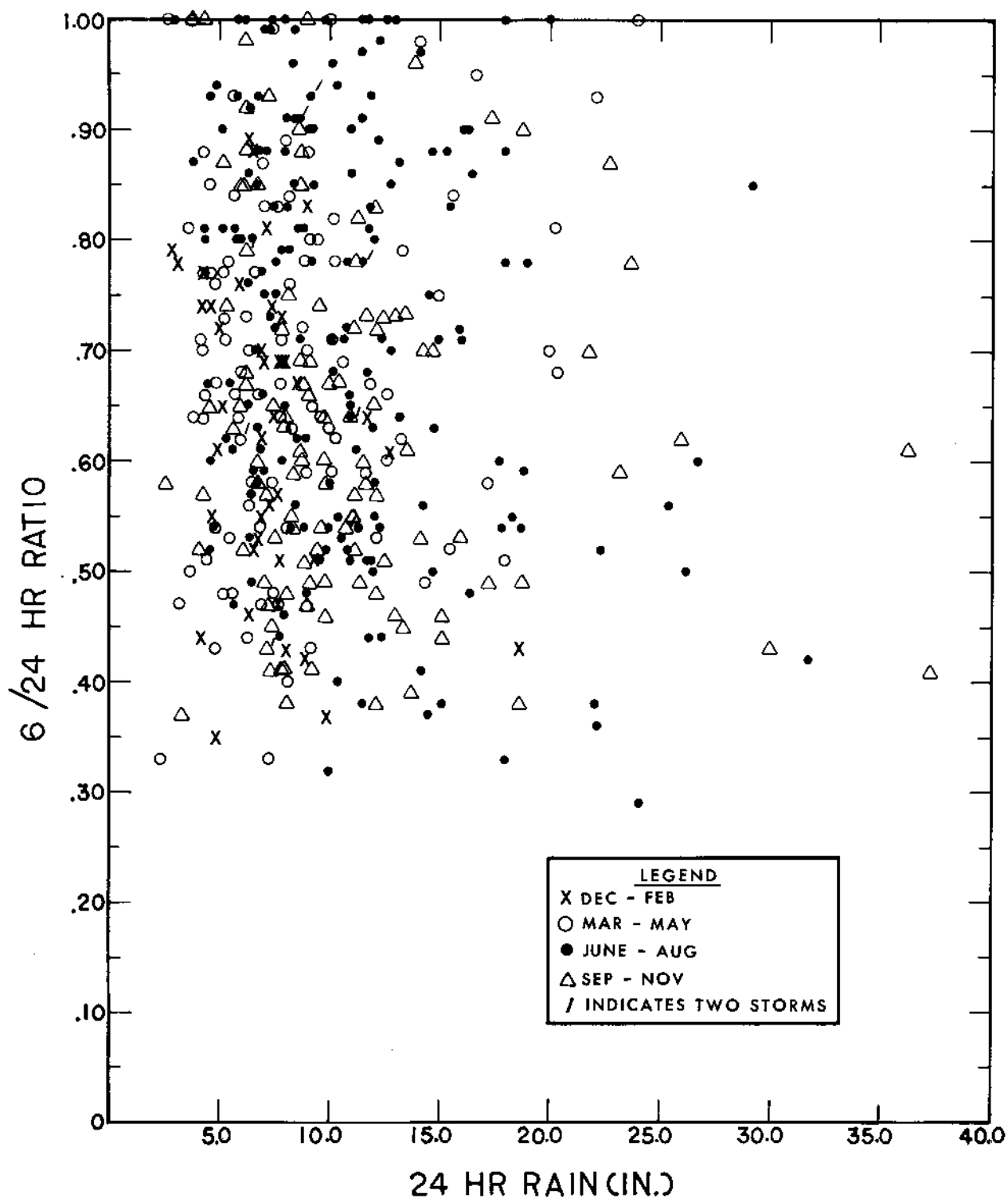
Figure 10b.--Within storm 6/24-hr rain ratios, July.

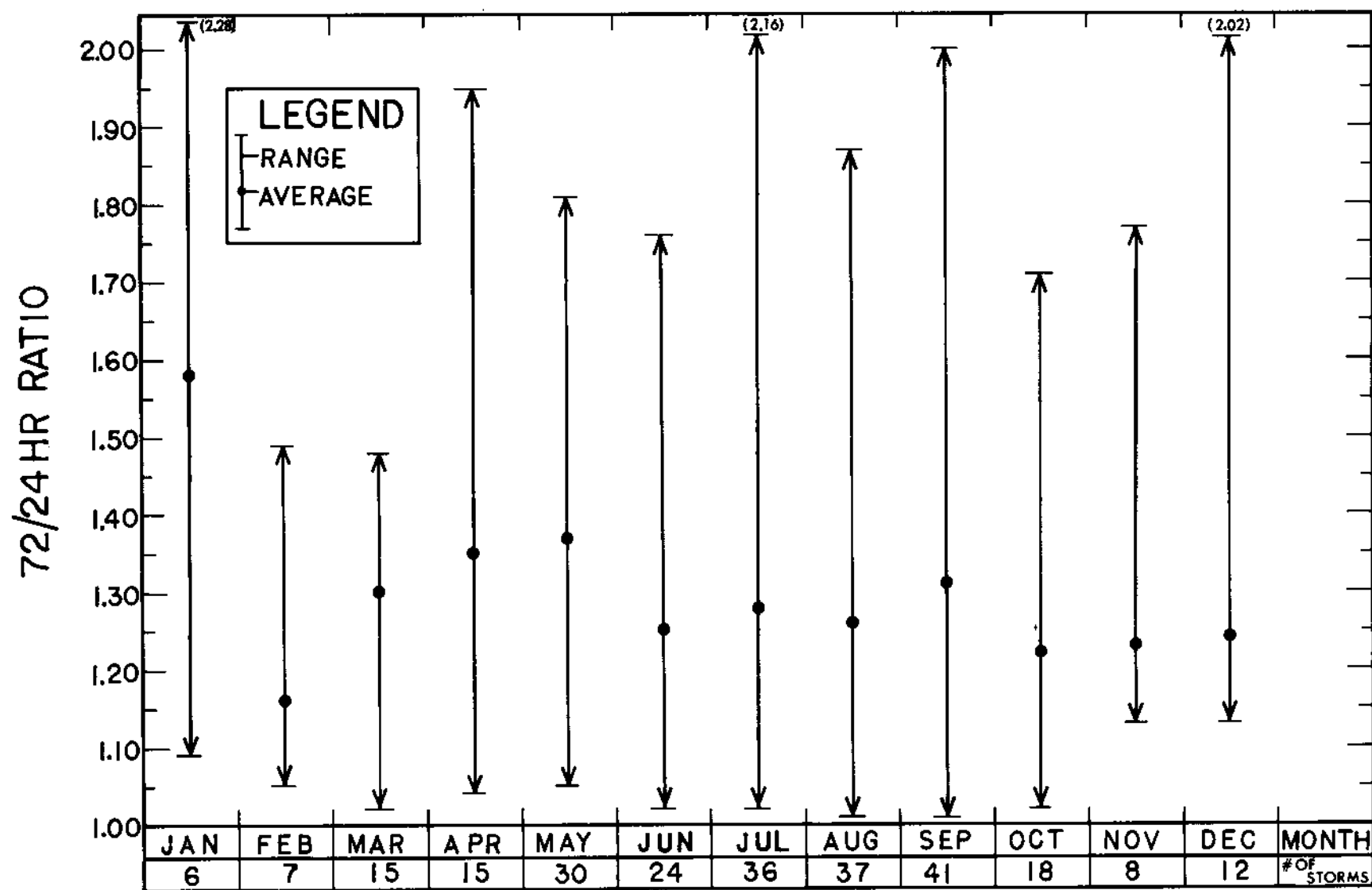Figure 11.—Within storm 6/24-hr rain ratios vs. magnitude of 24-hr depths.

Figure 12.--Seasonal variation of within storm 72/24-hr rain ratios for major storms in the study region.